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SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

1918

DAVID WHITE, CHIEF GEOLOGIST

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SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY, 1918.

NEW DETERMINATIONS OF CARBON DIOXIDE IN WATER OF THE GULF OF MEXICO.

By Roger C. Wells.

INTRODUCTION.

Although the carbon dioxide in sea water is the subject of a very extensive literature and many determinations of it have been made, recent advances in geochemistry have brought out new relations that require further determinations in order to show the connection, if any exists, between the history of the water, its temperature, its geographic location, the life it contains, and its saturation with calcium and magnesium compounds. In 1914 Clarke and Wheeler,[1] in a paper on crinoid skeletons, pointed out for the first time that the proportion of magnesium carbonate in crinoids is in some way dependent on temperature. This observation led to the publication of a number of papers presenting facts and theories bearing on the subject.[2]

Even earlier the investigations of Vaughan[3] on coral reefs and those of Branner[4] on the stone reefs of Brazil had led to the consideration of physical factors in the deposition of calcium carbonate in certain localities. Johnston has pointed out that the deposition of calcium carbonate by organic agencies may be closely related to the inorganic factors that determine how nearly saturated the water is with respect to that substance.

I have been enabled to make the determinations described in this paper through the interest and cooperation of T. W. Vaughan, of the United States Geological Survey, and H. F. Moore, of the Bureau of Fisheries. Mr. Vaughan pointed out the need of such determinations, particularly for American waters, and Mr. Moore authorized the collection of the samples, which were actually collected by W. W. Welsh and shipped in "citrate of magnesium" bottles to the chemical laboratory of the Geological Survey for analysis. It is a great pleasure to express appreciation for the assistance offered by all those who helped to make the study possible.

There is no question that the water of the Gulf of Mexico is essentially similar to that of the open ocean. An analysis of the salts in water off Loggerhead Key, near Florida, made by George Steiger in the chemical laboratory of the United States Geological Survey, is shown in Table 1, together with Dittmar's mean of 77 analyses of ocean water.

Table 1.—*Analyses of oceanic salts.*[a]

	1	2
Cl	55.24	55.29
Br	.17	.19
SO_4	7.54	7.69
CO_3	.34	.21
Na	30.80	30.59
K	1.10	1.11
Ca	1.22	1.20
Mg	3.59	3.72
	100.00	100.00

[a] Clarke, F. W., The data of geochemistry, 3d ed.: U. S. Geol. Survey Bull. 616, p. 123, 1916.

1. Salts in water of Gulf of Mexico; George Steiger, analyst.
2. Salts in ocean water, mean of 77 analyses; W. Dittmar, analyst.

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[1] Clarke, F. W., and Wheeler, W. C., The composition of crinoid skeletons: U. S. Geol. Survey Prof. Paper 90, pp. 33–37, 1915.

[2] Wells, R. C., The solubility of magnesium carbonate in natural waters: Am. Chem. Soc. Jour., vol. 37, pp. 1704–1707, 1915. Johnston, John, The solubility-product constant of calcium and magnesium carbonates: Idem, pp. 2001–2020. Wells, R. C., The solubility of calcite in water in contact with the atmosphere, and its variation with temperature: Washington Acad. Sci. Jour., vol. 5, pp. 617–622, 1915. Johnston, John, and Williamson, E. D., The complete solubility curve of calcium carbonate: Am. Chem. Soc. Jour., vol. 38, pp. 975–983, 1916. Johnston, John, Merwin, H. E., and Williamson, E. D., The several forms of calcium carbonate: Am. Jour. Sci., 4th ser., vol. 41, pp. 473–512, 1916. Johnston, John, and Williamson, E. D., The rôle of inorganic agencies in the deposition of calcium carbonate: Jour. Geology, vol. 24, pp. 729–749, 1916.

[3] Vaughan, T. W., The present status of the investigations of the origin of barrier coral reefs: Am. Jour. Sci., 4th ser., vol. 41, pp. 131–135, 1916. See also Carnegie Inst. Washington Pub. 133, pp. 173–177, 1910; Pub. 182, pp. 69–78, 1914; Year Book 14, p. 222, 1916, and Pub. 213, p. 227, 1918.

[4] Branner, J. C., Stone reefs on the northeast coast of Brazil: Geol. Soc. America Bull., vol. 16, pp. 1–12, 1905.

compare these figures with those obtained by other investigators.

Dittmar gives only four determinations on surface waters that are comparable with these, and all of them involve determinations of the "loosely combined" carbon dioxide, which were made by J. Y. Buchanan by a method that is not generally considered to yield exact results. However, they are as follows: [1]

TABLE 3.—*Dittmar and Buchanan's determinations of total carbon dioxide in surface waters.*

Sample No.	Locality.	Temperature.	CO_2.
		° C.	*Gram per liter.*
265	South Atlantic Ocean, lat. 22° 15′ S., long. 35° 37′ W	22.8	0.106
1573	South Atlantic Ocean, lat. 23° 27′ S., long. 13° 51′ W	25.1	.099
1581	South Atlantic Ocean, lat. 19° 55′ S., long. 13° 56′ W	24.7	.093
1687	North Atlantic Ocean, lat. 21° 23′ N., long. 31° 15′ W	22.8	.092

The results of the analyses of the 14 samples of Gulf water are in fair agreement with the four results of Buchanan's analyses of four samples of water from the surface of the open ocean.

TABLE 4.—*Dittmar and Buchanan's determinations of total carbon dioxide in deep waters.*

Sample No.	Locality.	Depth.	Temperature.	CO_2.
		Fathoms.	*° C.*	*Gram per liter.*
21	North Atlantic Ocean, lat. 23° 10′ N., long. 38° 42′ W	B 2,720	2.5	0.096
66	North Atlantic Ocean, lat. 19° 41′ N., long. 65° 7′ W	B 3,878	....	.112
120	North Atlantic Ocean, lat. 32° 54′ N., long. 63° 22′ W	B 2,360	2.4	.102
283	South Atlantic Ocean, lat. 29° 35′ S., long. 28° 9′ W	1,000	2.8	.109
353	Indian Ocean, lat. 46° 46′ S., long. 45° 31′ W	B 1,375	2.0	.118
378	Indian Ocean, lat. 60° 52′ S., long. 80° 20′ W	B 1,260	....	.128
383	Indian Ocean, lat. 65° 42′ S., long. 79° 49′ W	B 1,675	....	.149
(556)	South Pacific Ocean, lat. 14° 7′ S., long. 153° 43′ E	B 2,450	2.2	.101
594	West Pacific Ocean, lat. 5° 24′ S., long. 130° 37′ E	400	6.4	.094
791	North Pacific Ocean, lat. 11° 24′ N., long. 143° 16′ E	B 4,475	1.8	.086
912	North Pacific Ocean, lat. 36° 23′ N., long. 174° 31′ E	B 2,775	1.6	.090
1221	South Pacific Ocean, lat. 32° 36′ S., long. 137° 43′ W	B 2,375	1.7	.103
1300	South Pacific Ocean, lat. 38° 7′ S., long. 94° 4′ W	B 1,500	1.8	.102
678	West Pacific Ocean, lat. 5° 47′ N., long. 124° 1′ E	50	25.4	.081
1270	South Pacific Ocean, lat. 39° 13′ S., long. 118° 49′ E	B 2,250	1.4	.100
1313	South Pacific Ocean, lat. 38° 6′ S., long. 88° 2′ E	B 1,825	1.8	.108
1356	South Pacific Ocean, lat. 32° 50′ S., long. 77° 6′ W	50	12.0	.102
1388	South Pacific Ocean, lat. 42° 43′ S., long. 82° 11′ W	B 1,450	2.0	.112
1405	South Pacific Ocean, lat. 48° 27′ S., long. 74° 30′ W	B 345	7.8	.097
1438	South Pacific Ocean, lat. 52° 45′ S., long. 73° 46′ W	B 245	7.8	.102
1494	South Atlantic Ocean, lat. 35° 39′ S., long. 50° 47′ W	B 1,900	0.6	.098
1697	North Atlantic Ocean, lat. 26° 21′ N., long. 33° 37′ W	B 2,965	3.1	.092
1707	North Atlantic Ocean, lat. 32° 41′ N., long. 36° 6′ W	400	9.8	.091

The results obtained by combining the data of Dittmar and Buchanan for deeper waters are given in Table 4. Most of these were "bottom" waters (marked "B"), in which the total carbon dioxide is a little higher than in intermediate waters, for reasons that are discussed on page 11. The average for the bottom waters is 0.101; that for the intermediate waters is 0.095.

Tornöe found the average in 78 analyses of sea water to be 0.096 gram of carbon dioxide per liter, and results of the same order were obtained by Natterer.[2] Ruppin[3] found in the North Sea, at a depth of 5 meters, 0.091 gram of carbon dioxide per liter, and at 460 meters 0.095 gram.

Estimates by Dole of the total carbon dioxide in the Gulf water at Tortugas are given on page 2, but it should be noted that Dole did not directly determine the total carbon dioxide.

---

[1] *Challenger* Rept., Physics and chemistry, vol. 1, p. 215, 1884.

[2] Clarke, F. W., The data of geochemistry, 3d ed.: U. S. Geol. Survey Bull. 616, p. 144, 1916.

[3] Ruppin, E., Die Alkalinität des Meerwassers: Zeitschr. anorg. Chemie, vol. 66, p. 122, 1910.

Dole also obtained figures ranging from 0.055 to 0.109 in Biscayne Bay, the lowest being for water in Featherbed Bank, at 26.4° C., and he concluded from the salinities that evaporation was going on in the shallow water of the bay at the time his samples were taken. This action should also be accompanied by a loss of carbon dioxide, as actually observed. His average for the total carbon dioxide is 0.084 gram per liter.

THEORETICAL AMOUNT OF CARBON DIOXIDE IN SEA WATER.

If there are sources of carbon dioxide in the deep sea and the circulation of the water is slight, one might expect, theoretically, to find very considerable concentrations of carbon dioxide in such water. The pressure of the water would hold far larger proportions of any gas in solution than could remain dissolved at atmospheric pressure or smaller partial pressures. As very little is known about the extent to which moving creatures transfer carbon dioxide from place to place, the regulation of the concentration at depth would appear to be governed chiefly by the supply of carbon dioxide and by the rate of circulation of the water. At the surface, on the other hand, there is a tendency toward an equilibrium between the water and the atmosphere in respect to carbon dioxide, which Schlösing believed to be the governing factor in determining the carbon dioxide content of the atmosphere. This equilibrium can be studied in the laboratory and the results compared with those obtained by observations made in different parts of the ocean.

The equilibrium referred to may also involve the solution or deposition of calcium carbonate. A water in contact with calcium carbonate should theoretically dissolve more carbon dioxide from the atmosphere than one without access to calcium carbonate, but my own experiments on this point indicate that sea water exposed to a normal atmosphere gives off carbon dioxide at all temperatures above the very lowest, so that under surface conditions sea water in and between the temperate zones must be regarded as saturated with calcium carbonate. Therefore, laboratory experiments dealing with the equilibrium at ordinary temperatures yield the same results in the presence and in the absence of calcium carbonate.

In 1916 I performed two experiments with sea water to determine its total content of carbon dioxide at two definite temperatures, 1° C. and 28° C., after prolonged agitation of the water with outdoor air, an excess of calcite also being present in the water. The mean partial pressure of CO_2 was 0.000318 atmosphere, according to my determinations, and the two normalities found for CO_3+HCO_3 were 0.00236 and 0.00196, respectively. The result for total CO_2 at 1° C. was 0.101 gram per liter, and that at 28° C. was 0.078 gram. These results agree essentially with those calculated by the formula of Fox,[1] which gives 0.100 and 0.075, respectively.

Fox's formula, expressed in the terms used in the present discussion, is

$$\text{Total } CO_2 \text{ (grams per liter)} = na + pb$$

where n = the normality of CO_3+HCO_3, a = value given in Table 5, p = partial pressure of CO_2 in atmospheres, and b = value given in Table 6.

TABLE 5.—*Values of "a" for a solution of normality 1 at different temperatures and partial pressures of CO_2.*

p.	0°.	2°.	10°.	16°.	20°.	28°.
0.0002	40.42	40.08	38.70	37.69	37.00	35.64
.0003	42.09	41.79	40.58	39.67	39.07	37.86
.0004	43.11	42.83	41.71	40.87	40.31	39.19
.0005	43.77	43.51	42.47	41.69	41.17	40.13
.0006	44.37	44.15	43.24	42.56	42.11	41.21

TABLE 6.—*Values of "b" for different salinities and temperatures.*

[Chlorine in grams per thousand.]

Temperature (° C.).	Cl=0.	Cl=2.	Cl=10.	Cl=18.	Cl=20.
0	3.39	3.34	3.16	2.98	2.93
4	2.91	2.87	2.69	2.53	2.50
8	2.53	2.50	2.34	2.18	2.14
12	2.21	2.18	2.07	1.96	1.93
16	1.95	1.92	1.81	1.70	1.67
20	1.73	1.71	1.63	1.56	1.54
24	1.54	1.53	1.47	1.42	1.40
28	1.38	1.36	1.28	1.21	1.19

---

[1] Fox, C. J. J., On the coefficients of absorption of nitrogen and oxygen in distilled water and sea water and of atmospheric carbonic acid in sea water: Faraday Soc. Trans., vol. 5, p. 82, 1909.

COMPARISON OF RESULTS WITH EQUILIBRIUM CONDITIONS.

We are now in a position to compare the determinations of the total carbon dioxide in the samples of Gulf water with those representing equilibrium with the atmosphere. For this purpose I shall use 0.000318 atmosphere for the average carbon dioxide content of the atmosphere.[1] The normalities required in the calculation were determined as described in succeeding pages and are stated in Table 10. The comparison is shown in Table 7. Other data than this comparison (see p. 5) incline me to the view that surface sea water is generally fully saturated with respect to atmospheric conditions; if so, there is some small constant error in the determinations or in one of the factors on which the comparison is based. The most interesting feature of the comparison is the fact that the deeper waters seem to be as near to an equilibrium with the atmosphere, for their temperature, as the surface waters. That being true, what is the source of their carbon dioxide? It seems difficult to account for this adjustment by assuming that portions of the water have come from cold regions where they were in contact with the atmosphere and have transported carbon dioxide all that distance. A portion of water in passing from the polar regions might lose and gain carbon dioxide a number of times before arriving in the Gulf of Mexico. Has the water of the Gulf of Mexico access to more immediate sources of carbon dioxide than the atmosphere? Where the facts are so suggestive it is natural to seek for some hypothesis to explain them, and the most plausible one appears to be that living forms either carry or supply the carbon dioxide necessary to maintain equilibrium.

TABLE 7.—*Comparison of total carbon dioxide found in the Gulf waters with that representing equilibrium with the atmosphere.*

Sample No.	Locality.	Depth.	Temperature.	Total CO_2 found.	CO_2 for equilibrium.
		Meters.	°*C.*	*Gram per liter.*	*Gram per liter.*
2	Lat. 29° 38′ N., long. 87° 0′ W	0	18.9	0.093	0.094
3	.....do	50	19.4	.092	.098
5	.....do	150	13.3	.099	.099
6	.....do	210	10.2	.100	.100
7	Lat. 29° 53′ N., long. 87° 7′ W	0	20.0	.092	.095
8	.....do	25	20.1	.092	.094
9	.....do	50	19.6	.094	.098
10	.....do	100	18.2	.100	.098
11	.....do	130	15.8	.098	.099
12	Lat. 30° 5′ N., long. 87° 12′ W	0	18.3	.095	.097
13	.....do	20	18.4	.092	.097
14	4 miles northwest of Pensacola Light	0	16.7	.088	.091
15	.....do	10	16.4	.092	.097

The agreement between the last two columns of Table 7 is striking. In content of CO_2 the Gulf waters appear to be very nearly in equilibrium with the atmosphere—so nearly that the probable experimental error in the determinations of the normality of CO_3+HCO_3 would account for a positive or negative difference between many of the figures in the two columns. The same might be said of an error in the carbon dioxide content of the atmosphere used in the calculations or in the other factors entering into the comparison. From the data of Table 7 I do not feel warranted in concluding that any of the waters is either saturated or unsaturated with carbon dioxide under atmospheric conditions, but all the samples are evidently very near the condition of equilibrium.

Even Dittmar's results for carbon dioxide in the cold bottom waters of the ocean (Table 4) are approximately equal to the requirements for equilibrium with the atmosphere, although a few of the individual determinations show variations in one direction or the other. Inasmuch as the figures given by Dittmar include Buchanan's determinations and as the other factors on which the above comparisons rest are the work of many investigators, it must be admitted that the close approach of these waters to equilibrium with the atmosphere is really remarkable, as is also the fact that this relation is found in waters as deep as 3,000 fathoms. It seems as if organic agencies must contribute carbon dioxide to these deep waters, for it is difficult to see how currents in the ocean could possibly carry carbon dioxide from the surface in the colder regions to all the localities in the ocean that have been investigated and could produce by mere mixture samples approaching so closely the requirements for equilibrium. Buchanan[1] writes on this point:

---

[1] The higher value, 0.000353, recently published by Kendall, is for laboratory air. See Kendall, James, The specific conductivity of pure water in equilibrium with atmospheric carbon dioxide: Am. Chem. Soc. Jour., vol. 38, p. 1490, 1916.

> Down to nearly 2,000 fathoms life is still abundant; below this depth, however, the amount rapidly decreases till, at about 2,800 fathoms, it is, for carbonic acid producing purposes, practically extinct.

The preceding discussion suggests that the conditions maintained by organic and biochemical activity in the ocean correspond almost exactly with the physico-chemical conditions of equilibrium between sea water and a normal atmosphere at the temperatures involved.

DETERMINATION OF TOTAL CARBONATE AND BICARBONATE.

The determination of total carbonate and bicarbonate is sometimes referred to as that of the "alkalinity" and sometimes as that of the total base balancing carbonate and bicarbonate. Following Dittmar, investigators generally assume that there is no free base in sea water and that acid is consumed solely in setting free carbonic acid from carbonate and bicarbonate. The determination mentioned was made by titration with 0.02 normal sodium hydrogen sulphate. Methyl orange may be used as indicator, but the determinations were in fact carried out with paranitrophenol. The results obtained in titrating depend somewhat on the end point selected. The final reaction in the neutralization is

$$NaHCO_3 + NaHSO_4 = Na_2SO_4 + H_2CO_3$$

From this reaction it is evident that the indicator used should not give an indication for H_2CO_3 but for the first excess of $NaHSO_4$. Although carbonic acid is commonly considered to exert no action upon methyl orange, it really, as has long been known, develops a marked shade of red, and on this fact depends Küster's method of titrating to the same shade as that produced in water saturated with carbonic acid.[2] His method gives correct results with relatively concentrated solutions of bicarbonates. In the present case, however, the concentration of bicarbonate is very small and the solution is far from being saturated with carbon dioxide at the true end point. After neutralizing with acid sulphate there will be present about 0.0047 gram of CO_2 for 50 cubic centimeters of sea water. Evidently, the proper end point is indicated by the color produced by this amount of CO_2 in the same volume of water as that finally present in an actual determination. Experiment showed that this amount of CO_2 effects a scarcely perceptible change in methyl orange. If titration is carried to the first perceptible change in tint, or better, to a standard color produced by the amount of CO_2 known to be present, the acid used will correspond, as nearly as can be determined, to the total base balancing carbonate and bicarbonate.

In the hope of obtaining better results with some other indicator than methyl orange the behavior of paranitrophenol was studied. The indicator solution contained 1 gram in 250 cubic centimeters of water. The tests made are shown in Table 8.

TABLE 8.—*Comparisons of color in 50 cubic centimeter solutions in casseroles.*

Solution.	Color.
1a. Distilled water	No color.
2a. Distilled water, 0.0047 gram CO_2, 4 drops indicator.	Scarcely perceptible color at first; a faint color appears slowly on standing.
3a. Distilled water, 1 drop indicator.	Clearly perceptible color.
1b. Distilled water	No color.
2b. A solution of neutral sea salts (prepared by neutralizing the carbonates in actual sea water with the calculated quantity of acid and boiling out the carbon dioxide), 0.0047 gram CO_2, 4 drops indicator.	Scarcely perceptible color at first; a faint color appears slowly on standing.
3b. Distilled water, 1 drop indicator.	Clearly perceptible color.

---

[1] Buchanan, J. Y., Roy. Soc. London Proc., vol. 22, p. 483, 1874.

[2] Küster, F. W., Kritische Studien zur volumetrischen Bestimmung von karbonathaltigen Alkalilaugen und von Alkalikarbonaten: Zeitschr. anorg. Chemie, vol. 13, p. 127, 1897.

The shades of color produced by the indicator were found to depend considerably on the quality of the distilled water used. Freshly boiled water, after cooling, is perceptibly more alkaline than water as it comes regularly from the still or water that has stood in the laboratory some time, on account of the difference in carbon dioxide content. Solutions made up as described under 2a and 2b were used as furnishing the standard color for the proper end point. For the greatest possible accuracy it would appear that the preparation of the standard should be deferred until after the determination of total CO_2. It is possible that better results could be obtained in Nessler tubes than in casseroles, but the glass of certain Nessler tubes was found to be rather too soluble for the purpose. No error seemed to be introduced in the very weak solutions of CO_2 under investigation by working in casseroles, and the color showed up well in diffused daylight. However, it is doubtful if the results obtained with paranitrophenol were more accurate than those obtained with methyl orange.

As nearly as could be determined the titrations were significant to about 1 per cent of the quantities being titrated, so that the combined normality of carbonate and bicarbonate in sea water ought to be determinable within 1 per cent by this method. Practically, however, the attainment of such accuracy would probably require a number of titrations on each sample. As the small samples of water available for the determinations recorded in this paper did not permit more than two titrations, and some samples only one, any single result is probably not nearer the true value than 2 per cent.

The solution of $NaHSO_4$ used for titrating the samples of sea water, to determine the total base balancing carbonate and bicarbonate, was standardized with a solution containing sodium carbonate and bicarbonate in essentially the same proportion and concentration as in sea water. In this way the conditions at the end point were similar in both the standardization and the determinations. The results obtained in the standardization are shown in Table 9.

TABLE 9.—*Standardization of $NaHSO_4$ solution with solutions of $NaHCO_3$ and Na_2CO_3.*

$NaHCO_3$.	Na_2CO_3.	$NaHSO_4$.	Normality of $NaHSO_4$.
Gram.	*Gram.*	*c.c.*	
0.00794	0.00143	5.89	0.0206
.00794	.00143	5.87	.0207
.00794	.00143	5.82	.0209
.00794	.00143	5.81	.0209
.00794	.00143	5.92	.0206
.00794	.00143	5.86	.0207
Mean			.0207

The results of the titrations are shown in the fourth column of Table 10. They are expressed in terms of normality, a normal solu-

TABLE 10.—*Determinations of carbonate and bicarbonate in water from the Gulf of Mexico.*

Sample No.	Locality.	Temperature (°C.).	CO_3+HCO_3 normality.	HCO_3 normality.	CO_3 normality.
1	Lat. 25° 35′ N., long. 80° 6′ W.		0.00268	0.0021	0.0006
2	Lat. 29° 38′ N., long. 87° 0′ W.	18.9	.00239	.0018	.0006
3	do	19.4	.00250	.0017	.0008
4	do	18.5	.00242		
5	do	13.3	.00245	.0020	.0004
6	do	10.2	.00245	.0021	.0004
7	Lat. 29° 53′ N., long. 87° 7′ W.	20.0	.00242	.0018	.0007
8	do	20.1	.00239	.0018	.0005
9	do	19.6	.00250	.0018	.0007
10	do	18.2	.00249	.0020	.0005
11	do	15.8	.00249	.0020	.0005
12	Lat. 30° 5′ N., long. 87° 12′ W.	18.3	.00245	.0019	.0006
13	do	18.4	.00245	.0017	.0007
14	4 miles northwest of Pensacola Light	16.7	.00230	.0017	.0006
15	do	16.4	.00241	.0018	.0006
	Mean, exclusive of No. 1		.00244	.00185	.00058

tion being one containing 1 gram equivalent of reacting substance per liter—that is, as many grams as the molecular weight reduced to a univalent basis. As is mentioned on page 3, sample 1 had stood for most of the time from July, 1915, to April, 1917, in a green glass "acid" bottle with some air space. The other samples were collected in January, 1917, preserved in bottles with practically no air space, and analyzed in April, 1917. Without doubt it would have been better if the titrations could have been made on shipboard immediately after the samples were taken. The high value of the carbonates in sample 1 may be due to attack of the glass bottle. The figures for the other 14 samples may also be slightly high for the same reason, but if the difference between sample 1 and the others represents the effect of standing in glass for 17 months, the correction for any one of the 14 results is only about 2 per cent of its value, a correction just about equal to the possible experimental error.

DISCUSSION OF RESULTS FOR THE TOTAL CARBONATE AND BICARBONATE.

Dittmar made determinations of the "alkalinity"—that is, the combined carbonate and bicarbonate—in 130 samples of water collected on the *Challenger*.[1] It was his opinion that the results were unaffected by long preservation of the water in glass bottles. The mean of all his determinations gives a normality of 0.00249. The mean for the Gulf waters, as shown above, is 0.00244. Ruppin obtained on shipboard in the North Sea 0.00238. Dole's figures for the water at Tortugas (p. 2) give a normality of 0.00234.

Now, as pointed out in the introduction, there is a need for study of the relation between the solubility of calcium and magnesium compounds and temperature. In 1915 I investigated the solubility of magnesium and calcium carbonates in pure water and determined the relation between the solubility of calcite in water in contact with the atmosphere and the temperature. (For reference see p. 1.) Further determinations seemed desirable for sea water, and such determinations have now been made on a portion of the water collected at Fowey Rocks Light, outside Biscayne Bay, Fla. The water, in contact with an excess of calcite, was agitated by a current of outdoor air for long periods at different temperatures, and the dissolved carbonates were determined by titration with 0.02 normal $NaHSO_4$, methyl orange being used as indicator. The results obtained are shown in Tables 11 and 12.

TABLE 11.—*Determinations of total CO_3+HCO_3 when calcite is added to sea water at 1° C. and air passed daily.*

Time.	Carbonates per liter normality.
Start	0. 00247
10 days	.00246
12 days	.00241
14 days	.00238
33 days	.00239
40 days	.00236

TABLE 12.—*Determinations of total CO_3+HCO_3 when calcite is added to sea water at room temperature and air passed daily.*

Time.	Temperature (°C.).	Carbonates per liter normality.
Start	....	0. 00247
10 days	25	.00225
12 days	25	.00221
14 days	26	.00215
33 days	28	.00199
35 days	29	.00208
40 days	28	.00196

The results obtained show that under conditions otherwise similar there is a tendency for the colder sea water to retain more carbonate in solution than the warmer sea water. What was not expected, however, is the fact that the colder water did not dissolve fresh calcite but appears rather to have remained almost unchanged during the 40 days' run. In other words, sea water appears to be so far saturated with respect to calcium carbonate that in contact with the atmosphere at 1° C. it neither has nor acquires an appreciable solvent action on calcite. At higher temperatures it undergoes a slow diminution in its content of carbonates on being agitated in contact with outdoor air.

To compare with the above determinations, I had, fortunately, been able to make a few titrations at sea. At two points in the

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[1] Dittmar, W., *Challenger* Rept., Physics and chemistry, vol. 1, p. 124, 1884.

Caribbean Sea, about latitude 13° N., longitude 81° W., the normality of the carbonates was found to be 0.00236 and 0.00238 at 25° C. Water from the Pacific off Payta, Peru, at 24° C., gave 0.00226. These figures are a little higher than those found in the laboratory after a few days' agitation and suggest a condition of saturation, under atmospheric conditions, although they throw no light on the variations with temperature.

Let us now consider all the data available on surface sea water to see if the results show a definite relation between the normality of carbonate and bicarbonate and the temperature.

Of Dittmar's 130 results the 14 for surface waters are reproduced in Table 13, after recalculation to the terms used here.

It is difficult to see much if any regularity with regard to temperature in the results given in Table 13. There is a slight indication that the normality of CO_3+HCO_3 decreases with rising temperature, but the results are too few and too unreliable to show the relation with certainty.

TABLE 14.—*Ruppin's determinations of CO_3+HCO_3 for water of the North Sea, depth 5 meters.*

Date.	Temperature (° C.).	CO_3+HCO_3 normality.
Feb. 18, 1907	4.5	0.00236
May 6, 1907	6.0	.00236
May 10, 1907	6.2	.00232
May 8, 1907	6.4	.00240
May 5, 1907	6.7	.00237
May 12, 1906	7.5	.00242
May 19, 1906	9.1	.00241
Nov. 14, 1906	9.3	.00238
Do	9.4	.00238
May 11, 1906	9.4	.00242
Nov. 14, 1906	9.5	.00238
Do	11.4	.00239
Nov. 13, 1906	12.4	.00240
Aug. 17, 1906	15.1	.00232
Do	15.3	.00236
Aug. 15, 1906	15.9	.00239
Do	16.2	.00234
Mean	....	.00238

Apparently, then, although the variation in the normality of CO_3+HCO_3 with temperature can be shown in the laboratory, it is not very evident in published determinations for surface water of the open ocean.

TABLE 13.—*Dittmar's determinations of CO_3+HCO_3 for surface waters.*

Sample No.	Locality.	Temperature (° C.).	CO_3+HCO_3 normality.
384	Indian Ocean, lat. 65° 42′ S., long. 79° 49′ E.	−1.1	0.00255
1271	South Pacific Ocean, lat. 38° 56′ S., long. 116° 8′ W.	11.9	.00234
1471	South Atlantic Ocean, lat. 41° 39′ S., long. 54° 48′ W.	15.3	.00235
2	North Atlantic Ocean, lat. 27° 24′ N., long. 16° 55′ W.	18.0	.00286
9	North Atlantic Ocean, lat. 24° 22′ N., long. 24° 11′ W.	19.4	.00260
1700	North Atlantic Ocean, lat. 30° 20′ N., long. 36° 6′ W.	21.9	.00248
1687	North Atlantic Ocean, lat. 21° 33′ N., long. 31° 15′ W.	22.8	.00248
265	South Atlantic Ocean, lat. 22° 15′ S., long. 35° 37′ W.	22.8	.00260
327	Indian Ocean, lat. 36° 48′ S., 19° 24′ E.	22.8	.00253
1581	South Atlantic Ocean, lat. 19° 55′ S., long. 13° 56′ W.	24.7	.00250
1573	South Atlantic Ocean, lat. 23° 27′ S., long. 13° 51′ W.	25.1	.00246
201	North Atlantic Ocean, lat. 10° 25′ N., long. 20° 30′ W.	25.5	.00241
1127	South Pacific Ocean, lat. 3° 48′ S., long. 152° 56′ W.	26.1	.00240
668	Near Philippine Islands, lat. 9° 10′ N., long. 124° 25′ E.	27.2	.00234
	Mean	....	.00249

Further determinations were made in the North Sea by Ruppin on the *Poseidon.*[1] Some of his results are shown in Table 14.

In Ruppin's results, also, no relation between the carbonate content and the temperature can be discovered.

Analyses of some of the warmer and nearly inclosed seas, on the other hand, show a decrease in the carbonate content. Natterer[2] found that in the Red Sea, for instance, the carbonates are low and the deposition of solid carbonates takes place. It is evident that chiefly in such portions of the ocean or in the polar regions will there be found marked manifestations of the temperature effect on the normality of CO_3+HCO_3.

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[1] Ruppin, E., Die Alkalinität des Meerwassers: Zeitschr. anorg. Chemie, vol. 66, p. 122, 1910.

[2] Natterer, K., Monatsh. Chemie, vol. 20, p. 1, 1899.

In Dittmar's determinations for cold bottom waters, however, high values of the normality are found. But as the mean of his figures for the surface waters of Table 13, 0.00249, agrees with the mean of all his determinations, it follows that the intermediate samples actually show a lower normality of carbonates than either surface or bottom samples. I obtain from his data 0.00243 for 49 samples from intermediate depths. Moreover, the mean for 25 samples at temperatures below 11° is exactly the same as the mean for 24 samples at temperatures above 11°. The value 0.00243 would therefore appear to be the most representative value of the normality for the whole ocean. But the variation with temperature, except for the bottom samples, does not appear in Dittmar's results. Such a variation, however, is found in the Gulf waters. It may be that in the intermediate waters of the open ocean there is lacking a source of the bases or possibly of CO_2. On the bottom there may be a source of carbon dioxide in the decay of organic matter and of the bases in the inorganic material, which would explain high results for bottom samples. The slight excess in the CO_3+HCO_3 normality for the surface waters, however, is more difficult to account for. If it is due to additional bases, where do they come from? Possibly river water or organic life at the surface—such as algae—act as competent sources of the bases. The atmosphere or organic life could furnish the carbon dioxide, but in view of the experiments whose results are given in Tables 11 and 12 sea water does not appear to be in a condition to receive carbon dioxide from the atmosphere except at the very coldest temperatures. This leaves river water and organic life as the chief probable agencies contributing carbon dioxide to the surface waters of the ocean.

Table 15 contains a summary of the conclusions so far suggested concerning the total CO_2 and the normality of the bases balancing CO_3 and HCO_3 with reference to a condition of equilibrium with the atmosphere.

The conclusions concerning ocean water do not involve the greatest depths or the cold polar regions. It will be seen that by postulating a slight deficit of CO_2 and bases in the intermediate ocean waters these waters will be ready to increase their CO_2 if they come into contact with the bottom. As a matter of fact, however, they must be surrounded by extensive layers of water in which equilibrium prevails, as the surface and bottom concentrations are excessive. It is interesting to recall in this connection that the waters of the southern and western Pacific seem to be deficient in both carbon dioxide and bases balancing CO_3 and HCO_3. These very general conclusions are the best that can be drawn from all the evidence. In any actual series of samples, however, variations seem to occur which suggest that there may well be local variations due to organic activity that operates faster than the mixing of the water. Chemical tests are commonly made on comparatively small samples of the water, and it may be that greater constancy would be obtained if larger samples could be employed.

TABLE 15.—*Conclusions suggested from the investigation with reference to a condition of equilibrium with the atmosphere.*

	Depth.	CO_2.	Bases.
Ocean water of temperate regions down to 3,000 fathoms.	Surface	Slight excess	Slight excess.
	Intermediate	Slight deficit	Slight deficit.
	Bottom	Equilibrium or excess	Equilibrium or excess.
Gulf of Mexico water	Surface	Slight excess	Slight excess.
	Intermediate	Equilibrium	Equilibrium.

CALCULATION OF CARBONATE AND BICARBONATE.

The amounts of carbonate and bicarbonate present may first be calculated on the assumption that all the CO_2 found is combined as CO_3 and HCO_3 balancing bases. Thus, for water 7 in Tables 2 and 10 let x=normality of CO_3 and y=normality of HCO_3. Then

$$22x+44y=0.092$$
$$\text{and}\quad x+\quad y=0.00242$$

whence $y=0.0018$ and $x=0.0007$.

The results thus obtained for the 15 samples are shown in the last two columns of Table 10.

These results average, as they stand, 0.0018 for the bicarbonate normality and 0.0006 for the carbonate normality. Dole's average results for Tortugas water, obtained exclusively by titration methods, are 0.0016 and 0.0008, respectively (from 0.069 and 0.017 gram CO_2 in the two forms; see p. 2). From Dittmar's figure of 0.092 gram per liter for the total CO_2 in water of the North Atlantic at 22.8° C. (Table 3) and a normality of 0.00243 for $HCO_3 + CO_3$, I obtain 0.0018 and 0.0006 for the normalities of HCO_3 and CO_3, respectively, which are identical with the figures for the Gulf surface water, given in Table 10.

Let us next consider the magnitude of the error introduced by neglecting free carbon dioxide in the above calculations. The combination of Dole's mean values for CO_3 and HCO_3 with my mean value for the total CO_2 in surface Gulf water gives 0.006 gram per liter free CO_2. If this figure correctly represents the free CO_2 it would leave for sample 7, for example, $0.092 - 0.006 = 0.086$ gram CO_2 for the HCO_3 and CO_3. The calculation will then be as on page 11:

$$\begin{aligned} 22x + 44y &= 0.086 \\ \text{and}\quad x + y &= 0.00242 \end{aligned}$$

whence $y = 0.0015$, the normality of HCO_3, and $x = 0.0009$, the normality of CO_3 balancing an equivalent amount of base. These results differ markedly from those first obtained, namely, 0.0018 and 0.0007 for the normalities of HCO_3 and CO_3 respectively, and show clearly the order of the uncertainty involved in the concentrations under discussion. It should be noted, however, that the uncertainty is no longer in the amount of total CO_2 but only in the separate concentrations of the three forms in which the CO_2 is conventionally stated.

Johnston[1] states that the free carbon dioxide can be calculated if the total ion concentration of base, $[B^+]$, and the hydrogen-ion concentration, $[H^+]$, are known. The hydrogen-ion concentration can be determined by indicators or by the hydrogen electrode, but for several reasons it was not determined in the waters under scrutiny. The determination of $[B^+]$ involves some theory and uncertainty, and therefore a few illustrative calculations must suffice. Johnston gives the following figures for the free carbon dioxide when $[B^+]$ equals 0.001, which is comparable with the normality of HCO_3 found in sea water:

$[H^+]$.	Free carbon dioxide.
	Gram per liter.
10^{-6}	0.130
10^{-7}	.013
10^{-8}	.0013
10^{-9}	.00016

For $[B^+] = 0.01$ the corresponding values are ten times those given above..

Suppose that in sample 7 $[H^+] = 10^{-7}$ and $[B^+] = 0.002$, then free $CO_2 = 0.026$ gram per liter, leaving $0.092 - 0.026 = 0.066$ gram for $HCO_3 + CO_3$. The calculation will then be, as before,

$$\begin{aligned} 22x + 44y &= 0.066 \\ \text{and}\quad x + y &= 0.00242 \end{aligned}$$

whence $y = 0.0006$, the normality of HCO_3, and $x = 0.0018$, the normality of CO_3. These results may probably be regarded as extreme, as $[H^+]$ for sea water may be as low as or lower than 10^{-8}. If $[H^+] = 10^{-8}$ the free CO_2 will be 0.0028 gram, making $HCO_3 = 0.0016$ and $CO_3 = 0.0008$. If $[B^+]$ is less than 0.002 the quantity of free CO_2 will be less.

In a paper on the alkalinity of sea water Sörensen and Palitzsch[2] record determinations on a series of 24 samples of surface water from the Atlantic in which $[H^+]$ ranges from $10^{-8.34}$ to $10^{-7.81}$.

Recent determinations by Gaarder[3] yield values for $[OH^-]$ running from 0.5×10^{-7} to 25×10^{-7}; or, for 20°, $[H^+] = 1.3 \times 10^{-7}$ to 2.6×10^{-9}, which is somewhat less acid than that obtained by Sörensen and Palitzsch.

According to the determinations of McClendon[4] the water at Tortugas gives $[H^+] = 10^{-8.1}$ to $10^{-8.2}$.

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[1] Johnston, John, The determination of carbonic acid, combined and free, in solution, particularly in natural waters: Am. Chem. Soc. Jour., vol. 38, p. 955, 1916.

[2] Sörensen, S. P. L., and Palitzsch, S., Sur le mesurage de la concentration en ions hydrogène de l'eau de mer: Lab. Carlsberg Compt. rend. trav., vol. 9, p. 8, 1910.

[3] Gaarder, Torblorn, Hydroxyl number of pure water and sea water: Tidskrift Kemi Farm. Terapi, vol. 13, pp. 93-105, 135-137, 152-156, 169-172, 181-187, 198-201, 1916.

[4] McClendon, J. F., Experiments with Tortugas sea water: Carnegie Inst. Washington Year Book 15, p. 207, 1916. See also Mayer, A. G., Observations upon the alkalinity of the surface water of the tropical Pacific: Nat. Acad. Sci. Proc., vol. 3, p. 548, 1917.

Some further light is thrown on this problem by the comparison brought out in Table 7. It was shown that the Gulf waters appear to be very near equilibrium with the atmosphere. That being true, we may evaluate the free CO_2 by the second term of Fox's equation (p. 5). as that term is intended to represent the CO_2 present in physical solution, the average partial pressure of CO_2 for all the waters being taken as, say, 0.00032 atmosphere. The free CO_2 thus calculated ranges from 0.0005 to 0.0006 gram per liter. Although Henry's law is now known to be inapplicable with exactness to very dilute solutions of CO_2, the figures just given are far smaller than those calculated above for $[H^+] = 10^{-7}$ and 10^{-8}. Further investigation is needed to clear up this discrepancy.

In view of the uncertain factors here noted the figures in Table 10 may be allowed to stand as preliminary estimates of the proportions of carbonate and bicarbonate. In future determinations it will be desirable to evaluate $[H^+]$ along with the other determinations and correct for the free CO_2 as far as possible. It would obviously be incorrect to calculate the CO_3 and HCO_3 separately from the total CO_2 without correcting for the free CO_2 when the total CO_2 is exceptionally high and the total $HCO_3 + CO_3$ low, but such high total CO_2 seems to be the exception in warm ocean water. If we assume a mean value of 0.003 gram per liter of free CO_2 in all the samples of Gulf water analyzed, the mean values for the HCO_3 and CO_3 normalities for the Gulf water would be 0.0017 and 0.0007 respectively. As a matter of fact, however, the free CO_2 varies from one sample to another, like the other concentrations, and a complete statement for each sample would require the determination of at least three unknown quantities—better four, in order to check the results.

An examination of the results for the carbonate and bicarbonate given in Table 10 shows that there is a slight increase of the bicarbonate concentration and a slight decrease of the carbonate concentration indicated with increase in depth, or, one may say, with decrease in temperature. The variation is not great but appears to be real; if it is real, an increase in temperature corresponds to a decrease in total CO_2, in the total $CO_3 + HCO_3$, and in HCO_3, and an increase in CO_3. These relations correspond to the known effect of temperature on the solubility of carbon dioxide in water, on the solubility of calcium carbonate in water, and on the hydrolysis of carbonates. An increase in total CO_2 therefore corresponds to an increase in HCO_3 but not in CO_3.

For the sake of completeness, Buchanan's determinations, made during the cruise of the *Challenger*, of the amount of carbon dioxide eliminated from sea water by boiling are presented for comparison. There has long been some uncertainty as to the exact significance of the results,[1] but they must be of value as comparative determinations, having all been made by the same method. I have studied Buchanan's results for surface waters with reference to the equilibrium that should exist between the waters and the atmosphere in respect to carbon dioxide, and I find the clearest indication of a relation between the temperature of the water and its content of loosely combined carbon dioxide. Apparently, also, there is a difference between the Atlantic and the Pacific waters, but if the results for the surface waters are arranged solely according to temperature the general relation is that the amount of loosely combined carbon dioxide is greater in the colder waters. (See Table 16 and fig. 1.)

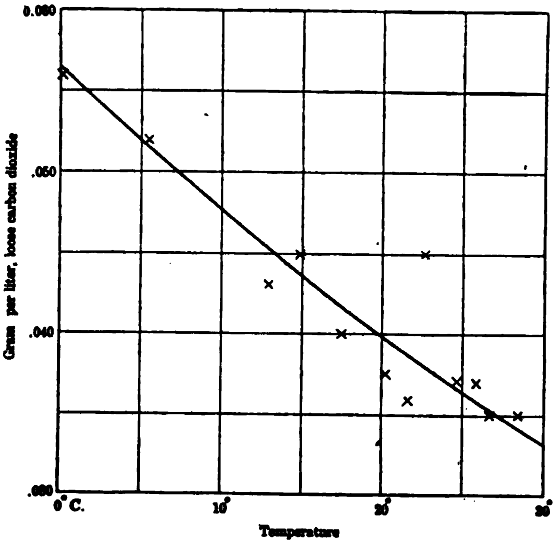

FIGURE 1.—Curve showing variation of loosely combined carbon dioxide in surface sea water with temperature. The crosses represent the 12 means given in Table 16.

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[1] *Challenger* Rept., Physics and chemistry, vol. 1, p. 103, 1884. Presumably Buchanan's results give the CO_2 of bicarbonate together with free CO_2 if present.

TABLE 16.—*Buchanan's determinations of loosely combined carbon dioxide in surface ocean water, arranged according to the temperature of the water.*

Sample No.	Locality.	Temperature.	Loose carbon dioxide.
		°*C.*	*Gram per liter.*
389	South Indian Ocean, lat. 64° 52′ S., long. 83° 12′ E	−1.7	0.049
386	South Indian Ocean, lat. 66° 29′ S., long. 78° 18′ E	− .7	.056
396	South Indian Ocean, lat. 64° 1′ S., long. 87° 41′ E	.4	.049
382	South Indian Ocean, lat. 64° 2′ S., long. 79° 55′ E	.7	.066
387	South Indian Ocean, lat. 65° 10′ S., long. 78° 42′ E	.7	.052
380	South Indian Ocean, lat. 62° 22′ S., long. 80° 4′ E	1.1	.064
	Mean	.1	.056
415	South Indian Ocean, lat. 53° 13′ S., long. 109° 23′ E	4.3	.052
354	South Indian Ocean, lat. 46° 16′ S., long. 48° 27′ E	5.0	.054
364	South Indian Ocean, lat. 46° 53′ S., long. 51° 52′ E	5.0	.047
360	South Indian Ocean, lat. 46° 8′ S., long. 49° 40′ E	5.8	.051
417	South Indian Ocean, lat. 50° 54′ S., long. 118° 3′ E	7.2	.054
	Mean	5.5	.052
1272	South Pacific Ocean, lat. 38° 43′ S., long. 112° 31′ W	11.8	.037
1287	South Pacific Ocean, lat. 39° 19′ S., long. 101° 19′ W	12.5	.042
1378	South Pacific Ocean, lat. 42° 19′ S., long. 84° 47′ W	12.7	.047
1390	South Pacific Ocean, lat. 45° 31′ S., long. 78° 9′ W	12.7	.049
1314	South Pacific Ocean, lat. 38° 19′ S., long. 84° 25′ W	13.6	.037
1375	South Pacific Ocean, lat. 39° 41′ S., long. 86° 33′ W	13.9	.046
	Mean	12.9	.043
1462	South Atlantic Ocean, lat. 42° 32′ S., long. 56° 29′ W	14.2	.039
1374	South Pacific Ocean, lat. 38° 59′ S., long. 83° 53′ W	14.2	.051
1301	South Pacific Ocean, lat. 37° 55′ S., long. 93° 56′ W	14.7	.035
1366	South Pacific Ocean, lat. 36° 17′ S., long. 83° 50′ W	15.5	.048
1367	South Pacific Ocean, lat. 36° 58′ S., long. 83° 40′ W	15.5	.047
471	South Pacific Ocean, lat. 37° 2′ S., long. 160° 48′ E	15.6	.050
	Mean	15.0	.045
1342	South Pacific Ocean, lat. 33° 20′ S., long. 74° 24′ W	16.9	.036
1352	South Pacific Ocean, lat. 32° 50′ S., long. 77° 6′ W	17.5	.038
497	South Pacific Ocean, lat. 31° 23′ S., long. 177° 48′ W	17.8	.059
949	North Pacific Ocean, lat. 37° 35′ N., long. 163° 46′ W	17.9	.029
	Mean	17.5	.040
504	South Pacific Ocean, lat. 28° 25′ S., long. 177° 93′ W	19.4	.041
276	South Atlantic Ocean, lat. 27° 54′ S., long. 31° 22′ W	19.4	.043
1508	South Atlantic Ocean, lat. 36° 55′ S., long. 44° 50′ W	20.0	.034
1699	North Atlantic Ocean, lat. 29° 50′ N., long. 35° 55′ W	20.5	.034
836	North Pacific Ocean, lat. 28° 23′ N., long. 137° 45′ E	20.8	.032
267	South Atlantic Ocean, lat. 24° 43′ S., long. 34° 17′ W	21.0	.042
	Mean	20.2	.038
136	North Atlantic Ocean, lat. 37° 52′ N., long. 42° 1′ W	21.1	.053
117	North Atlantic Ocean, lat. 34° 51′ N., long. 63° 59′ W	21.4	.045
910	North Pacific Ocean, lat. 35° 55′ N., long. 171° 54′ E	21.7	.035
826	West Pacific Ocean, lat. 24° 47′ N., long. 138° 34′ E	21.8	.021
926	North Pacific Ocean, lat. 36° 59′ N., long. 178° 56′ W	21.9	.027
512	South Pacific Ocean, lat. 23° 18′ S., long. 173° 26′ W	21.9	.036
	Mean	21.6	.036
75	North Atlantic Ocean, lat. 27° 49′ N., long. 64° 59′ W	22.2	.048
1687	North Atlantic Ocean, lat. 21° 33′ N., long. 31° 15′ W	22.8	.037
1684	North Atlantic Ocean, lat. 17° 49′ N., long. 28° 28′ W	22.7	.038
265	South Atlantic Ocean, lat. 22° 15′ S., long. 35° 37′ W	22.8	.059
119	North Atlantic Ocean, lat. 32° 54′ N., long. 63° 22′ W	23.3	.042
	Mean	22.8	.045

TABLE 16.—*Buchanan's determinations of loosely combined carbon dioxide in surface ocean water, arranged according to the temperature of the water*—Continued.

Sample No.	Locality.	Temperature.	Loose carbon dioxide.
		°C.	*Gram per liter.*
990	North Pacific Ocean, lat. 30° 51′ N., long. 154° 23′ W.	23.9	0.019
68	North Atlantic Ocean, lat. 21° 26′ N., long. 65° 16′ W.	24.4	.046
515	South Pacific Ocean, lat. 20° 9′ S., long. 176° 47′ W.	24.5	.061
1581	South Atlantic Ocean, lat. 19° 55′ S., long. 13° 56′ W.	24.7	.038
572	West Pacific Ocean, lat. 11° 37′ S., long. 142° 59′ E.	25.0	.027
1573	South Atlantic Ocean, lat. 23° 27′ S., long. 13° 51′ W.	25.1	.035
1590	South Atlantic Ocean, lat. 14° 59′ S., long. 13° 42′ W.	25.1	.035
256	South Atlantic Ocean, lat. 14° 51′ S., long 37° 1′ W.	25.3	.033
	Mean	24.7	.037
209	North Atlantic Ocean, lat. 7° 7′ N., long. 16° 11′ W.	25.7	.043
817	West Pacific Ocean, lat. 21° 17′ N., long. 140° 40′ E.	25.8	.025
214	North Atlantic Ocean, lat. 6° 15′ N., long. 16° 5′ W.	25.9	.038
539	South Pacific Ocean, lat. 16° 32′ S., long. 163° 12′ E.	25.9	.032
228	North Atlantic Ocean, lat. 1° 47′ N., long. 24° 26′ W.	26.0	.043
216	North Atlantic Ocean, lat. 4° 34′ N., long. 13° 52′ W.	26.1	.043
	Mean	25.9	.037
215	North Atlantic Ocean, lat. 5° 48′ N., long. 14° 20′ W.	26.2	.046
581	West Pacific Ocean, lat. 7° 13′ S., long. 134° 18′ E.	26.4	.039
557	South Pacific Ocean, lat. 13° 50′ S., long. 151° 49′ E.	26.7	.036
661	West Pacific Ocean, lat. 12° 21′ N., long. 122° 15′ E.	26.7	.037
1097	North Pacific Ocean, lat. 7° 26′ N., long. 149° 22′ W.	26.8	.029
682	North Pacific Ocean, lat. 4° 33′ N., long. 127° 6′ E.	26.9	.025
	Mean	26.6	.035
602	West Pacific Ocean, lat. 1° 42′ S., long. 127° 7′ E.	27.9	.042
760	North Pacific Ocean, lat. 4° 21′ N., long. 145° 18′ E.	28.4	.030
1662	North Atlantic Ocean, lat. 7° 10′ N., long. 15° 10′ W.	28.6	.034
	Mean	28.3	.035

We are now in a position to make a statement of the constituents of the salts in Gulf water, say for the surface at a temperature of 18° to 20° C., which shall include the total CO_2 as carbonate and bicarbonate. Based on Steiger's analysis (Table 1), it is given in Table 17, which includes also a similar statement, based on Dittmar's analysis, for ocean water, say the open Atlantic at moderate depth at 18° to 20°.

TABLE 17.—*Revised analyses of salts in the Gulf of Mexico and ocean water.*

	Gulf of Mexico.	Ocean.
Cl	55.23	55.21
Br	.17	.19
SO_4	7.54	7.68
HCO_3	.31	.31
CO_3	.05	.05
Na	30.79	30.54
K	1.10	1.11
Ca	1.22	1.20
Mg	3.59	3.71
	100.00	100.00

Table 18 gives the results of a calculation of the chemical equivalence of the basic and acid radicles that constitute the salts in the water based on the percentages of the constituents shown in Table 17.

TABLE 18.—*Equivalence of basic and acid salt constituents whose percentages are given in Table 17.*

Basic radicles.	Reacting values.		Acid radicles.	Reacting values.	
	Gulf.	Ocean.		Gulf.	Ocean.
Na	1.339	1.328	Cl	1.558	1.557
K	.028	.028	Br	.002	.002
Ca	.061	.060	SO_4	.157	.160
Mg	.295	.305	HCO_3	.005	.005
			CO_3	.002	.002
Sum of basic equivalents	1.723	1.721	Sum of acid equivalents	1.724	1.726

SUMMARY.

The determinations of carbon dioxide in water of the Gulf of Mexico recorded in this paper show that the total carbon dioxide increases with depth—that is, with decreasing temperature—and the amounts found are very near though slightly below those required for equilibrium with atmospheric carbon dioxide, as calculated by Fox's equation. Determinations of the total concentration of base held in balance with the carbonate and bicarbonate radicles were also made; this quantity apparently increases slightly with decreasing temperature. The data presented do not permit an exact evaluation of the "free" carbon dioxide in the water, but a consideration of the uncertain factors upon which computation of the free carbon dioxide rests indicates that the amount is probably so small in the Gulf water that no appreciable error is made by expressing the total carbon dioxide found as a mixture of carbonate and bicarbonate. At any rate, the constituents thus determined, taken in the form of salts and dissolved in the appropriate amount of pure water, would reproduce the Gulf water under the conditions existing when the samples were collected.

GEOLOGY OF NORTHEASTERN MONTANA.

By Arthur J. Collier.

INTRODUCTION.

REGION EXAMINED.

A large region in northeastern Montana has never been thoroughly explored by geologists, owing to the fact that it is a part of the Great Plains and the belief that it is too monotonous and uninteresting to tempt anyone to turn aside from the pronounced geologic features a little farther west, for which Montana is noted. This region includes parts of Sheridan, Valley, Phillips, and Blaine counties. Its investigation was begun by Smith[1] in 1908, when he made a geologic survey of the Fort Peck Indian Reservation. Beekly[2] explored a strip of land along the Montana-North Dakota line from Missouri River to the international boundary, and Bauer[3] examined the townships in which Plentywood and Scobey are situated.

Their results are here included with those of the writer, who during the field seasons of 1915 and 1916 was engaged in an investigation of the lignite resources of the remainder of this region, which extends from a line within 12 miles of the Montana-North Dakota boundary westward about 200 miles. In the western half of the region very little lignite was found, and the work was of the nature of a hasty reconnaissance extending from the international boundary to Missouri River. A few townships are covered by old land surveys, and the corners are located with difficulty, other townships are still unsurveyed, and in some the work has not yet been completed; though the corners were found in the field, no plats were available. The townships in the eastern part of the region have been surveyed by the General Land Office within the last six or seven years. In the examination of the lignite beds in this area the plane table and telescopic alidade were in constant use, and the locations of the outcrops were tied to the section corners, which are usually marked by iron posts and are easily found.

ACKNOWLEDGMENTS.

W. T. Thom, jr., and R. F. Baker were assigned to the field party in 1915, and H. R. Bennett accompanied the writer in 1916. Edwin T. Conant was employed as teamster and assistant during both seasons. Much of the information contained in this report is the result of the faithful work done by these men.

W. C. Alden, who in 1916 began an investigation of the glacial features of eastern Montana, visited the party in the field and has frequently been consulted in the office. He has made many valuable suggestions, used in the preparation of this paper.

Acknowledgment is also due to Mr. Barnum Brown, of the American Museum of Natural History, for suggestions made in the course of the field season of 1916.

As the work in many parts of the region was more or less of a reconnaissance nature the only available maps were township plats made by the General Land Office. The Bowdoin, Saco, Hinsdale, and Cherry Ridge topographic maps of the United States Geological Survey; the maps to be published by the International Boundary Commission; the topographic maps of the Fort Peck Indian Reservation made by the General Land Office in connection with the township surveys and published by the Geological Survey; and the maps published by the Missouri River Commission have all been used in preparing this report.

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[1] Smith, C. D., The Fort Peck Indian Reservation lignite field, Mont.: U. S. Geol. Survey Bull. 381, pp. 40–59, 1910.

[2] Beekly, A. L., The Culbertson lignite field, Valley County, Mont.: U. S. Geol. Survey Bull. 471, pp. 319–358, 1912.

[3] Bauer, C. A., Lignite in the vicinity of Plentywood and Scobey, Sheridan County, Mont.: U. S. Geol. Survey Bull. 541, pp. 293–315, 1914.

The base map (Pl. I) is compiled from the township plats, with additions from the few topographic maps available and the field notes made by the writer and his assistants.

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1875.

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McConnell discovered the interesting Oligocene mammal remains in the Cypress Hills, a few miles north of the international boundary, and Cope's report is on the fossil remains of the region.

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Collier, A. J., and Thom, W. T., jr., The Flaxville gravel and its relation to the other high-terrace gravels of the northern Great Plains: U. S. Geol. Survey Prof. Paper 108, pp. 179-184 (Prof. Paper 108-J).

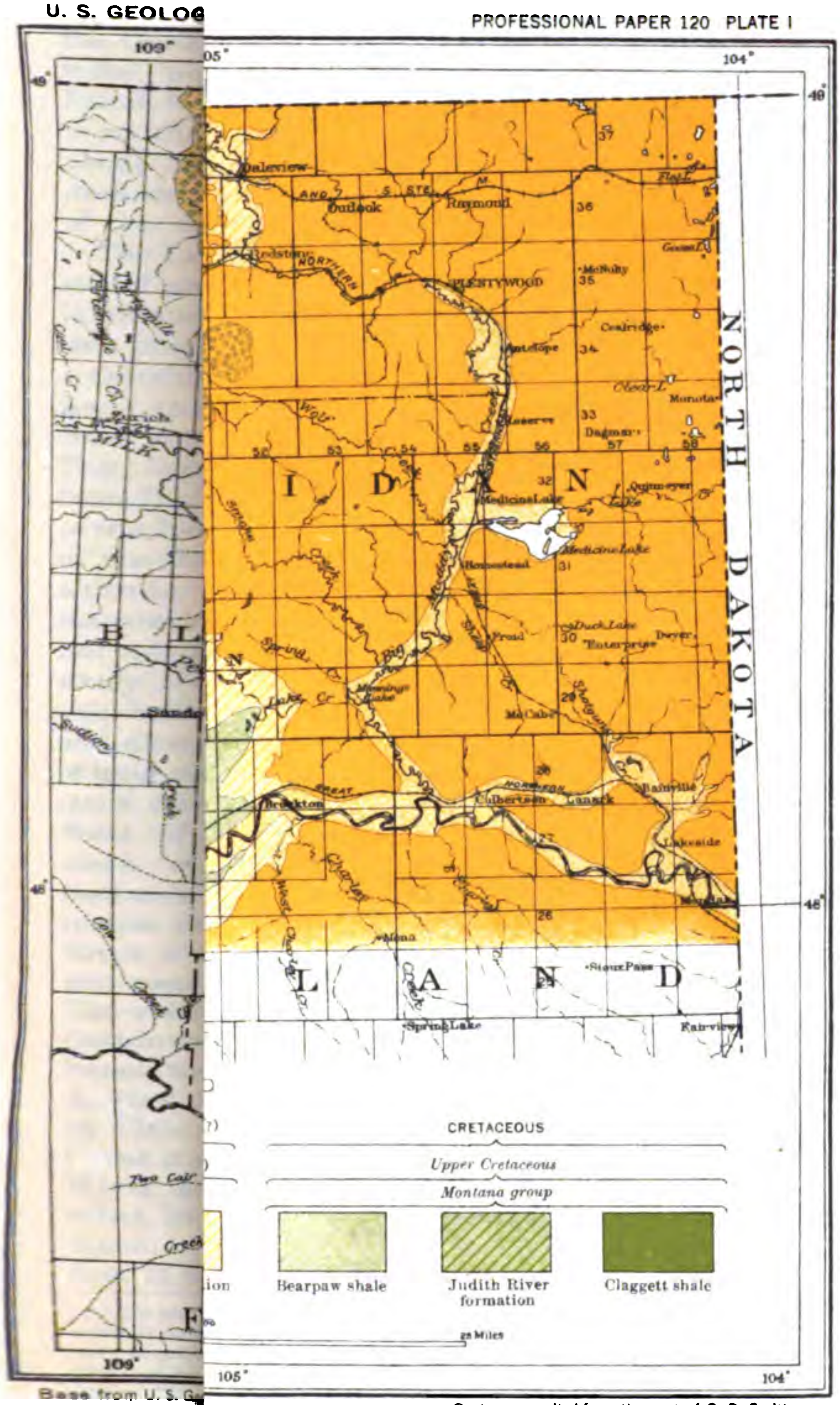
SURFACE FEATURES.

The region here described is a part of the Great Plains of North America. By this designation it is not intended to imply that the whole area consists of only one plain, for in fact there are at least three levels at which remnants of fairly well marked surfaces approaching plains can be discovered and between which there are more or less irregular slopes and escarpments. It can be assumed that at some very remote time the whole of the Great Plains constituted one plain, which was subsequently elevated and probably warped. The increased slope made it possible for the streams to sink their channels into the plain and as time went on to destroy most of its even surface by the headward cutting of the tributaries. Other periods of uplift and erosion have made possible the production of partial plains below the original one, until the region to-day is marked by a series of terraces or remnants of these plains. Adjacent to the southwest corner of the region described are the high peaks of the Little Rocky Mountains, which owe their origin to a totally different cause, namely, an intrusion of igneous rocks with which the underlying strata not elsewhere exposed are brought to the surface. Except for the Little Rocky Mountains the relief between the lowest point and the highest in this region is about 1,400 feet.

The highest points are in a series of plateaus near the Canadian line which are capped and protected from erosion by gravel. The plateau in the western part of the region stands at

U. S. GEOLOG

PROFESSIONAL PAPER 120 PLATE I



Geology compiled from the work of C. D. Smith, A. L. Beekly, C. A. Bauer, and A. J. Collier
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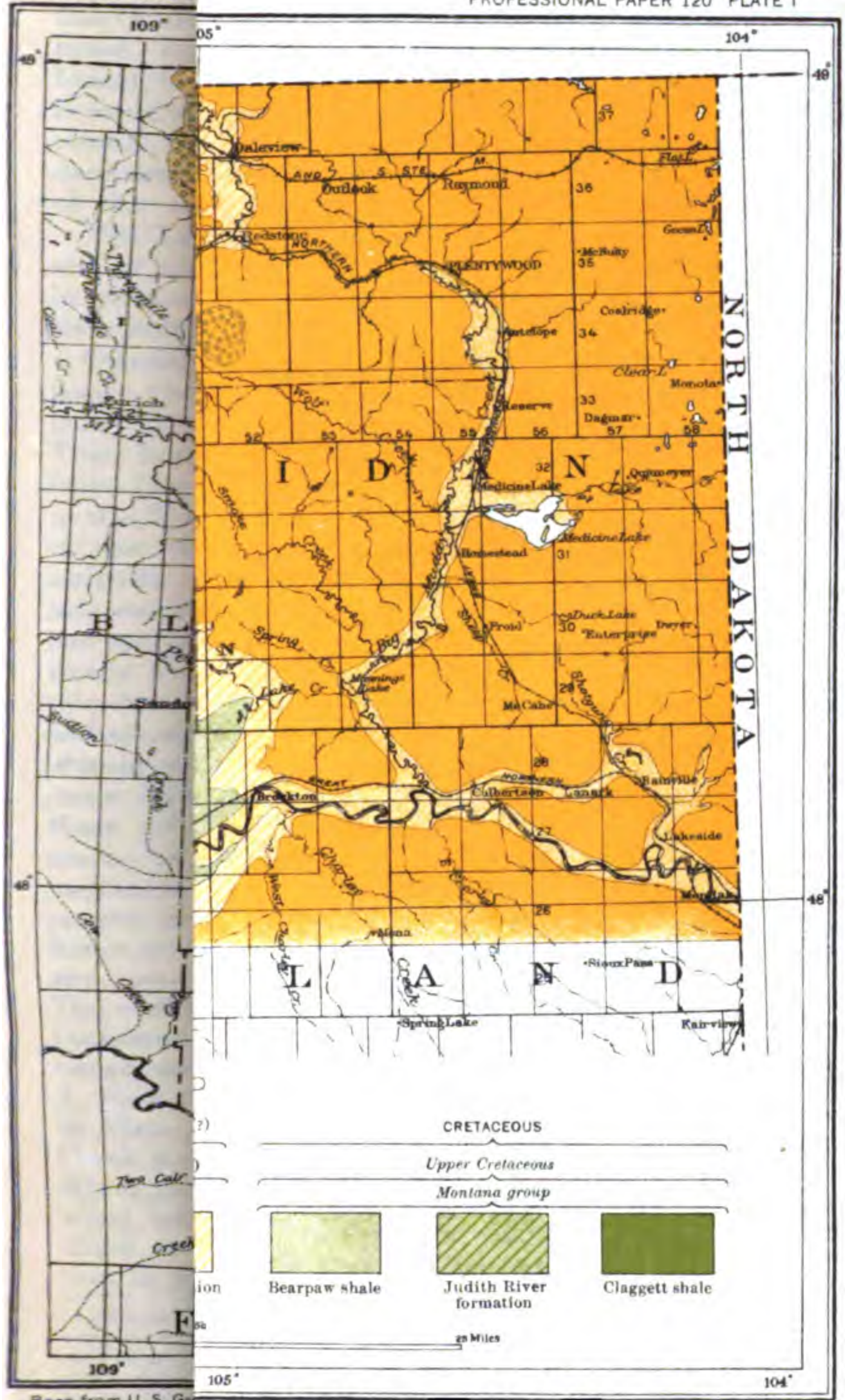
U. S. GEOLOG

PROFESSIONAL PAPER 120 PLATE I



Base from U. S. G

Geology compiled from the work of C. D. Smith, A. L. Beekly, C. A. Bauer, and A. J. Collier
Surveyed in 1908-16

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3,000 to 3,400 feet above the sea, as is indicated on the Cherry Ridge topographic map of the Geological Survey; east of it, for about 30 miles, no remnants of the high plateau are found, but in the neighborhood of Opheim there is another extensive plateau at an altitude of about 3,100 feet, east of which the elevation declines to about 2,700 feet in a plateau south of the town of Redstone.

The Larb Hills,[1] near Missouri River, also consist of an undulating plateau about 3,000 feet in altitude but differing from the plateau farther north in not having a thick gravel cover.

Outside of the areas occupied by these plateaus there is a marked bench of rolling land from 200 to 500 feet below the higher level. This bench can be seen to good advantage from Big Muddy Creek, northeast of Redstone, to the North Dakota line, as shown in the maps of the Boundary Commission, and ranges in altitude from 2,300 to 2,500 feet. At the international boundary the Big Muddy Valley has steep walls rising 260 feet to the comparatively level plain. West of Big Muddy Creek this bench continues with varying altitudes, and along the forks of Poplar River it consists of long slopes extending from the upper escarpment down within 200 feet of the river level. West of Opheim it consists of level-topped areas, of sloping grass-covered hills, and of badlands in which the shale is exposed. It ranges in altitude from 2,500 feet near Milk River to 3,000 feet at the international boundary near the crossing of Frenchman Creek. The valleys of Rock, Frenchman, Whitewater, Cottonwood, and other creeks cut across this bench and are especially deep near Milk River. A view of the gorge of Rock Creek is given in Plate II, *A*, and the valley of Cottonwood Creek is shown in Plate III, *A*. South of Milk River the elevated areas are generally somewhat lower, and the streams cutting across them occupy broad valleys from 100 to 400 feet in depth.

The valleys of Missouri and Milk rivers, ranging in altitude from 1,900 to 2,300 feet and lying from 100 to 500 feet below the level of the bench just described, together with the valleys of the smaller streams, constitute the lowest land in this region. The valley of Milk River is bordered by pronounced bluffs. It is in places several miles in width and was probably formed by a much larger stream than that which now occupies it. Calhoun[2] is authority for the statement that this valley was once occupied by Missouri River and that it was completely filled with ice during the glacial epoch so that the river was forced to cut for itself a new valley (the present course) 50 miles to the south.

The present valley of Missouri River near the mouth of the Musselshell is cut from 300 to 500 feet in the bench described and is not more than 3 miles across from rim to rim. (See maps published by the Missouri River Commission.) The river flows eastward in this narrow valley for many miles to the mouth of Big Dry Creek, in whose former valley it flows back to its original channel at the mouth of Milk River.

The effect produced by the moving of the continental ice sheet across this region is interesting and varied. In some areas the evidence of glaciation is almost entirely lacking, but even in such areas, if the surface has not been covered by deposits made since the glacial epoch, boulders of granite brought from the far-away shores of Hudson Bay, or large bodies of boulder clay, in part from the same source, can be found here and there. In addition to this evidence there are several glacial moraines marked by small irregularly placed lake beds separated by rounded hills. There are two large areas of this kind near the Canadian boundary—one in the eastern part of the region and the other extending from Whitewater Creek to the west side of the region mapped.

A description of the surface would not be complete without some reference to the Little Rocky Mountains, adjacent to the southwestern part of the region. These mountains, as has been shown by Weed and Pirsson,[1] are of a peculiar type in that they have a central core of very old rocks covered by a mass of porphyry (a laccolith) intruded at some time very much later than the formation of the sedimentary rocks and are flanked by the upturned edges of the deep-seated strata. They furnish the only clue that can be obtained in this region to the strata that lie far beneath the surface. The Black Hills of South Dakota and Wyoming[2] present a much better known example of this form of mountain uplift, and the Little Rocky Mountains can be described as a miniature reproduction of the Black Hills. On the Little Rocky Mountains there is a comparative abundance of timber, not only yellow pine and cedar but in many places fir, tamarack, and lodgepole pine.

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[1] The name Larb Hills has been applied to the uplands immediately south of Saco and has been published on the Bowdoin, Saco, and Hinsdale topographic maps of the United States Geological Survey. That this is an error is affirmed by many of the old inhabitants of the region. Messrs. Henry Carpenter and L. W. Gibson, who resided near the Missouri for many years, assert that the name was first applied to a relatively small area east of Timber Creek. It is applied to the whole group of highlands near Missouri River on the map by Calhoun published in U. S. Geol. Survey Prof. Paper 50.

[2] Calhoun, F. H. H., The Montana lobe of the Keewatin ice sheet: U. S. Geol. Survey Prof. Paper 50, pp. 38-42, 1906.

SETTLEMENT OF THE REGION.

From the days of Lewis and Clark (1804–1806) to the completion of the Northern Pacific Railway (1883) Missouri River was the great northern route of communication between the East and the West. Steamboats plied regularly on its muddy waters, bringing in supplies of all kinds and taking out pelts that the great fur companies had collected from the Indians and trappers. At that time many forts were built on the banks of the river to guard against attacks by the Indians, and one of the most important of these was Fort Union, which stood in this area opposite the mouth of Yellowstone River.

The building of the first railway ended the river traffic, and as the region adjacent to the international boundary was out of the ordinary line of travel, it was little visited until the completion of the Great Northern Railway about 1889. Up to that time the only inhabitants were Indians, trappers, traders, and woodcutters for the river steamers. After the building of the Great Northern Railway the country was practically given over to the raising of cattle and sheep. The railway stations became distributing points and have been the principal settlements for many years. Small irrigation plants have been established at many of these places, the principal crop being blue-joint hay. The Milk River irrigation project of the Reclamation Service, begun many years later, has improved large areas of low-lying land. About seven years ago a tide of new life in the guise of "dry land" homesteaders set in and is still swelling, though the more desirable land has been occupied. To meet this sweep of immigration, townships have been surveyed, branch railroads built or projected, and new towns established. The best land, from the farmer's point of view, is that on the flat surfaces of the higher plateaus, where the soil is easily worked and produces good crops of grain and flax. The bench lands are usually more rolling in character and are generally strewn with glacial boulders which must be gathered up before plowing. The soil on the benches in the eastern part of the region is derived largely from sandy formations and is easily cultivated and fully equal to that of the plateaus. (See Pl. II, *B*.) Large areas in the western part are underlain by shale, which forms a gumbo soil difficult to cultivate and on which the surface forms are more varied, but there are at many places large areas in which the invasion of ice during the glacial epoch has left a sandy soil that is easily tilled. The new homestead law, passed in 1917, which enables the settler to acquire 640 acres of land for grazing, will certainly encourage further settlement and will force the abandonment of the methods of the old stock-raising days.

The principal towns in this region are Culbertson, Poplar, Wolf Point, Glasgow, Vandalia, Hinsdale, Saco, and Malta, on the main line of the Great Northern Railway; Plentywood and Scobey, on a branch of the Great Northern; Outlook and Whitetail, on the St. Paul, Minneapolis & Sault Ste. Marie Railway; and Glentana and Opheim, on proposed railroads not yet built.

STRATIGRAPHY.

GENERAL SECTION.

The sedimentary rocks range from the pre-Cambrian core of the Little Rocky Mountains to the Recent alluvium of the existing streams. The source of the information regarding the rock from the pre-Cambrian to the Carbonifer-

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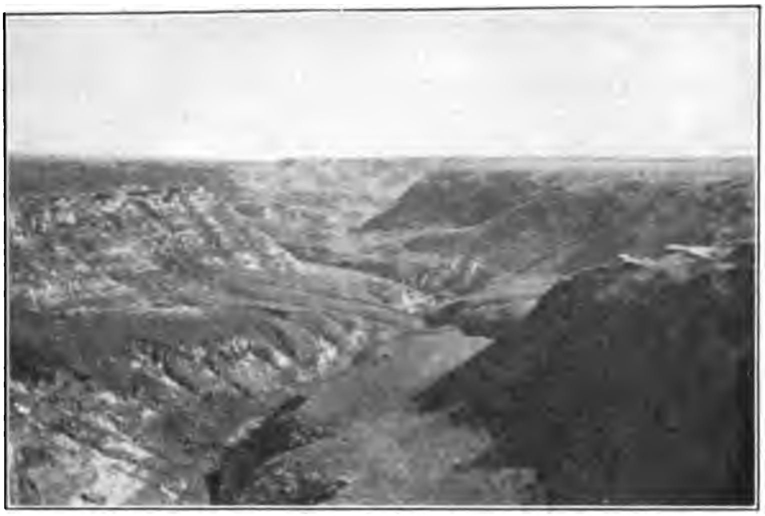
[1] Weed, W. H., and Pirsson, L. V., Geology of the Little Rocky Mountains: Jour. Geology, vol. 4, pp. 399-428, 1896.

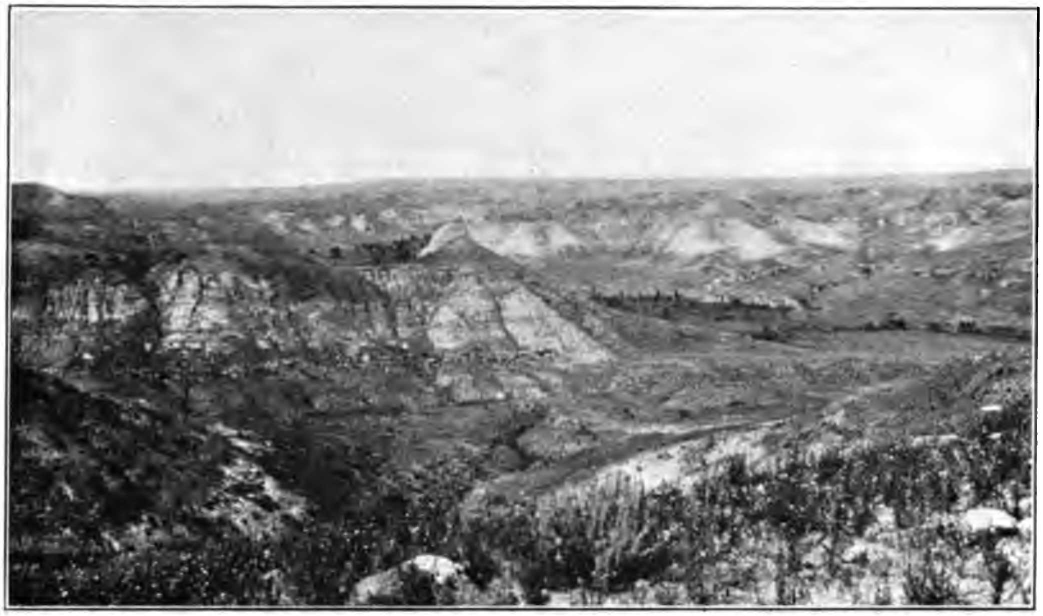
[2] Darton, N. H., U. S. Geol. Survey Geol. Atlas, Sundance folio (No. 127), 1905.



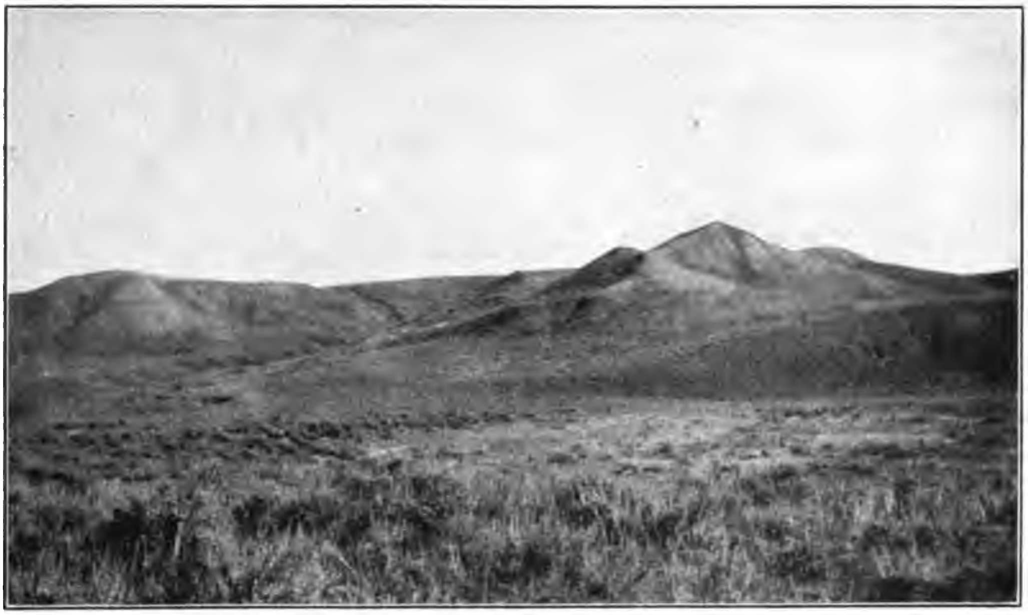
A. GORGE OF ROCK CREEK, VALLEY COUNTY, MONT.

B. GRAIN FIELD NEAR SCOBEY, MONT.

C. CAMP IN THE FOOTHILLS OF THE LITTLE ROCKY MOUNTAINS, PHILLIPS COUNTY, MONT.



A. VIEW UP THE VALLEY OF COTTONWOOD CREEK, PHILLIPS COUNTY, MONT.



B. BADLANDS OF BEARPAW SHALE NEAR LISMAS, MONT.

ous is an article by Weed and Pirsson,[1] from which the following remarks on the rocks below the Carboniferous are adapted. The section from the Carboniferous to the Claggett shale of the Cretaceous system was examined during the field season of 1916. Only one measurement of the section exposed was made, and it may be found to be more or less inaccurate owing to undetected variations in the dip. The areal distribution of the formations is shown in figure 2.

The descriptions of the formations above the Claggett shale are the results of work done by the writer and his assistants in 1915 and 1916, and the areal distribution of these formations is shown in Plate I. The geologic section is as given on page 22.

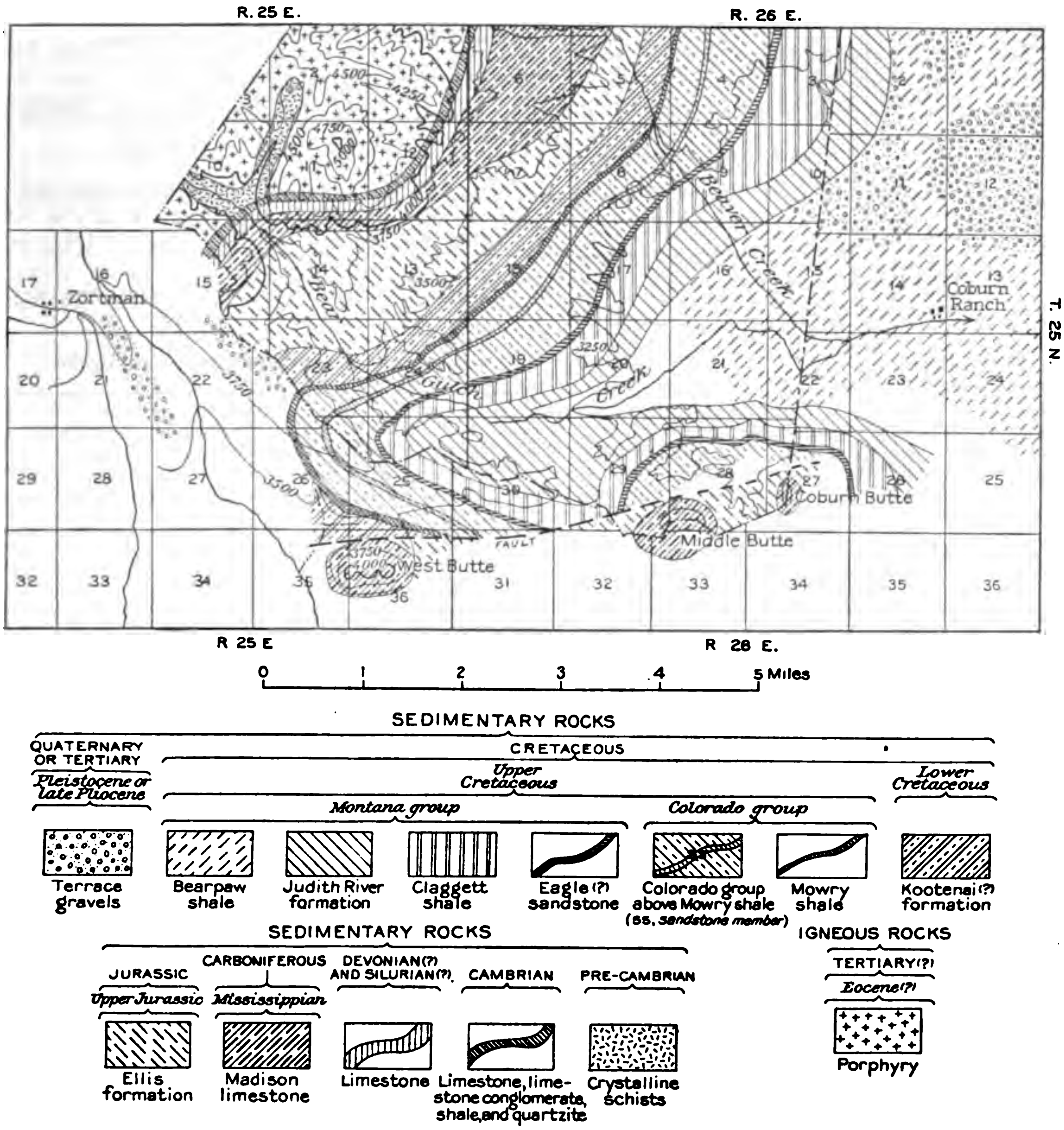


FIGURE 2.—Sketch map of the geology of T. 25 N., Rs. 25 and 26 E. principal meridian, Mont.

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[1] Weed, W. H., and Pirsson, L. V., op. cit., pp. 399-428.

Section of formations in northeastern Montana.

System.	Series.	Group and formation.		Thickness (feet).	Character.
Quaternary.	Recent.				Sandy soil derived from Flaxville gravel, Fort Union, Lance, and Judith River formations. Gumbo soil derived from the Bearpaw and Claggett shales.
					Alluvium deposited in the flood plains of streams.
		Unconformity			
	Pleistocene.				Scattered boulders, till, and moraines.
					Gravel deposited in Milk River valley by preglacial Missouri River.
		Unconformity			
Quaternary or Tertiary.	Pleistocene or late Pliocene.				Gravel and silt north of Malta. Gravel on benches around Little Rocky Mountains.
		Unconformity			
Tertiary.	Early Pliocene or Miocene.	Flaxville gravel.		0–100	Gravel, sand, and clay, in some places cemented with calcite.
		Unconformity			
	Eocene.	Fort Union formation.		0–1,400	Yellowish sandstone and shale carrying beds of lignite.
Tertiary)?).	Eocene(?).	Lance formation.		180–200	Somber-colored shale and sandstone; lignite beds.
				80–200	Yellowish sandstone and shale.
....	....				
Cretaceous.	Upper Cretaceous.	Montana group.	Bearpaw shale.	800–1,000	Dark-gray shale; marine fossils; gumbo soil.
			Judith River formation.	400–425	Light-colored shale and sandstone; marine and fresh-water fossils; a somewhat sandy soil.
			Claggett shale.	750	Dark-gray shale, marine fossils, gumbo soil.
			Eagle (?) sandstone.	100	Light-colored sandstone present in Little Rocky Mountains but probably absent in Bowdoin dome and points west.
		Colorado group.		875	Bluish-gray to black shale.
				60±	Light-colored sandstone capped by thin layer of fossiliferous limestone.
				325	Dark-blue shale.
			Mowry shale.	100	Platy siliceous shale; weathers into porcelain-like débris.
	Lower Cretaceous.	Kootenai (?) formation.		825	Variegated shale interbedded with yellow and brown sandstone.
Jurassic.	Upper Jurassic.	Ellis formation.		200	Massive cross-bedded sandstone.
				200–300	Thin-bedded limestone and shale.
		Unconformity			
Carboniferous.	Mississippian.	Madison limestone.			Massive fossiliferous limestone. Thin-bedded limestone.[a]
Devonian (?) and Silurian(?).					Dark-gray and black fetid limestone.[a]
Cambrian.					Thin-bedded limestone.[a] Limestone conglomerate. Green shale. Quartzite.
Pre-Cambrian.					Black crystalline amphibole schist.[a]

[a] Adapted from Weed, W. H., and Pirsson, L. V., Geology of the Little Rocky Mountains: Jour. Geology, vol. 4, pp. 399-423, 1896.

PRE-CAMBRIAN ROCKS.

The core of the Little Rocky Mountains is composed of crystalline schist (fig. 3). The type most usually seen is a fine-grained, dense, compact black crystalline amphibole schist or amphibolite, which splits into fragments with bright surfaces. These rocks are reported by Weed and Pirsson as being clearly altered sandstones. They are certainly older than the Cambrian.

PORPHYRY LACCOLITH.

Overlying the pre-Cambrian core of the Little Rocky Mountains is a great lenslike mass or laccolith of porphyry (see fig. 3), which was intruded at a much later date and which arched the overlying rocks into a dome. The exact thickness of the porphyry has not been measured, but it is known to be 300 or 400 feet on the principal summits, where it rests upon black mica schist into which the streams have cut their gorges. The outlying buttes, like those shown in figure 3, probably represent local thickenings or possibly separate intrusions of porphyry from which, in many places, the overlying rocks have not been eroded.

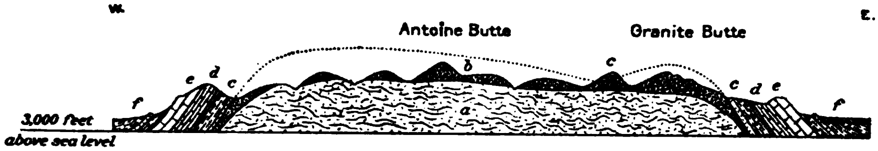

FIGURE 3.—Section of the laccolith of the Little Rocky Mountains, Mont. (After Weed and Pirsson.) *a*, Crystalline schists; *b*, granite porphyry; *c*, Cambrian; *d*, Silurian (?) and Devonian (?); *e*, Carboniferous; *f*, Mesozoic.

CAMBRIAN SYSTEM.

Cambrian rocks, of which Weed and Pirsson give the following section, lie upon the laccolith just described.

Section of Cambrian rocks in Little Rocky Mountains, Mont.

	Feet.
Thin-bedded fissile limestone, pure limestone with shell remains alternating with impure sandy and more or less conglomeratic beds; general color gray	25
Limestone conglomerates and gray shale, greenish sandy layers alternating with pure argillaceous beds. There are some thin beds of limestone from which a few fossils were taken	40
Green shale carrying limestones and conglomerates	50
Green or copperas-colored shale	30
Interval in which the beds are not exposed	300
Quartzite changing to conglomerate near the base, generally flesh-colored, mostly brecciated and rusty	75
	520

Fossils collected by Weed and Pirsson from the limestone mentioned in the section were examined by Walcott, who identified *Ptychoparia oweni* Hall and *Obolella nana* Meek and Hayden. Both are Middle Cambrian forms.

SILURIAN AND DEVONIAN SYSTEMS (?).

Above the Cambrian rocks (figs. 2 and 3) are slate-colored and black fetid limestones possessing the general characteristics of the Silurian and Devonian rocks as developed in the Rocky Mountain region to the west. No fossils were found in these rocks, and their tentative reference to the Silurian and Devonian systems by Weed and Pirsson is based on their lithologic character and position between the Cambrian and Carboniferous rocks.

CARBONIFEROUS SYSTEM.

MADISON LIMESTONE.

The Carboniferous rocks (fig. 2) consist of several hundred feet of somewhat thinly bedded limestone at the base, capped by several hundred feet of massive, thick-bedded limestone which appears to be characteristic of the Mississippian Madison limestone throughout the Rocky Mountain region. From this formation Weed and Pirsson report five species of fossils collected by E. S. Dana and pronounced lower Carboniferous by Whitfield.[1]

Several collections of fossils, made principally by H. R. Bennett, have been examined by G. H. Girty, who has identified at least 22 species and who declares that the formation is identical with the Madison limestone of other parts of Montana. His report follows:

Sec. 33, T. 25 N., R. 24 E. (lot 19):
- Zaphrentis sp.
- Syringipora surcularia.
- Rhipidomella aff. R. burlingtonensis.
- Schuchertella chemungensis?
- Productus ovatus.
- Productus aff. P. viminalis.
- Productus gallatinensis?
- Productus (Strophalosia?) sp.
- Spirifer aff. S. incertus.

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[1] Ludlow, William, Reconnaissance from Carol, Mont., to Yellowstone National Park, p. 129, Washington, 1876.

Sec. 33, T. 25 N., R. 24 E.—Continued.
- Brachythyris suborbicularis?
- Martinia? sp.
- Syringothyris carteri.
- Athyris lamellosa.
- Euomphalus sp.

Sec. 36, T. 25 N., R. 15 E. (lot 21):
- Zaphrentoid corals.
- Euomphalus sp.

Same location as above but lower in section (lot 22):
- Triplophyllum sp.
- Schuchertella chemungensis.
- Chonetes ornatus.
- Spirifer centronatus.
- Reticularia cooperensis.

Sec. 27, T. 25 N., R. 26 E. (lot 25):
- Leptaena analoga.
- Schuchertella chemungensis.
- Chonetes loganensis.
- Chonetes ornatus.
- Chonetes logani.
- Pustula n. sp.
- Productus ovatus.
- Productus arcuatus?
- Productus sp.
- Camarotoechia metallica.
- Camarotoechia sp.
- Dielasma aff. D. burlingtonense.
- Spirifer centronatus.
- Syringothyris carteri.
- Martinia rostrata.
- Spiriferina solidirostris.
- Reticularia cooperensis.
- Composita humilis.
- Cliothyridina cf. C. crassicardinalis.
- Platyceras sp.

Same location as above but higher in the section (lot 26):
- Triplophyllum sp.
- Schuchertella chemungensis.
- Chonetes logani.
- Chonetes ornatus.
- Spirifer centronatus.
- Spiriferina solidirostris.

Sec. 22, T. 25 N., R. 25 E. (lot 36):
- Triplophyllum sp.
- Fenestella, several sp.
- Pinnatopora sp.
- Batostomella sp.
- Rhombopora sp.
- Cystodictya sp.
- Schuchertella chemungensis?
- Schizophoria? sp.
- Chonetes ornatus.
- Chonetes logani.
- Chonetes loganensis.
- Productus arcuatus?
- Pustula n. sp.
- Camarotoechia aff. C. herrickana.
- Camarotoechia metallica.
- Spirifer centronatus.
- Camarotoechia mysticensis.
- Camarotoechia sp.
- Spiriferina solidirostris.

Sec. 22, T. 25 N., R. 25 E.—Continued.
- Reticularia cooperensis.
- Martinia rostrata.
- Composita sp.
- Cliothyridina incrassata?
- Eumetria aff. E. vera.
- Entolium shumardianum.
- Platyceras sp.
- Griffithides? sp.

It is probable that all six collections are of lower Mississippian age and belong to the Madison limestone, though they show several different faunal facies. Lots 22, 25, 26, and 36 are typical Madison faunas. Lot 21 shows too little for definite identification of the horizon. Lot 19 suggests a typical Burlington more than a typical Madison fauna, yet the Madison is in part of Burlington age, and collections from it sometimes show a markedly Burlington facies, like this one.

The Madison limestone is the most striking formation surrounding the Little Rocky Mountains. It is the encircling girdle of the mountains, in which the picturesque canyons are cut. Seen from a distance it appears like a great horizontal bed, but on closer examination it is found to be turned up at high angles and its edge cut by deep canyons. The three small outlying domes shown in figure 2 are made up wholly of this limestone.

JURASSIC SYSTEM.

ELLIS FORMATION.

Overlying the Madison limestone in the Little Rocky Mountains is a formation made up of shale and shaly and sandy limestone (fig. 2), which was described by Weed and Pirsson. A fauna from it, determined by T. W. Stanton as Jurassic, consisted of the following forms:

- Ammonite fragments of undetermined species.
- Belemnites densus Meek and Hayden.
- Pleuromya subcompressa Meek.
- Astarte meeki Stanton.
- Modiola subimbricata Meek.
- Gryphaea calceola var. nebrascensis Meek and Hayden.

Larger collections from this formation were made by H. R. Bennett during the field season of 1916 and were identified by J. B. Reeside, jr., as follows:

9832. Sec. 27, T. 25 N., R. 26 E. From shale above thin-bedded shale and limestone which overlies the Madison limestone:
- Ostrea strigilecula White.
- Belemnites densus Meek and Hayden.
- Pleuromya sp.?
- Indeterminable casts of pelecypods.

9832. Sec. 27, T. 25 N., R. 26 E.—Continued.
    - Small ammonite distinct from described American forms but evidently a cardioceratid.
9833. Same locality as 9832 but lower in the section:
    - Gryphaea calceola var. nebrascensis Meek and Hayden.
    - Ostrea strigilecula White.
    - Pleuromya subcompressa Meek.
    - Astarte? sp.
    - Rhynchonella sp. undescribed.
    - Belemnites densus Meek and Hayden.
    - Serpula sp. undet.
    - Fragment of an undescribed ammonite, suggesting Perisphinctes.
9834. Sec. 7, T. 25 N., R. 26 E. From thin-bedded limestone above the Madison limestone:
    - Fragments of an ammonite suggesting Perisphinctes.
    - Gryphaea calceola var. nebrascensis Meek and Hayden.
    - Pleuromya subcompressa Meek.
    - Pholadomya kingi Meek.
    - Lima cinabarensis Stanton.
    - Cucullaea? sp. cf. C. haguei Meek.
    - Camptonectes extenuatus Meek and Hayden.
    - Thracia? sp. like T. arcuata Meek but very much larger.
    - Rhynchonella sp. undescribed.
    - Belemnites densus Meek and Hayden.
    - Astarte meeki Stanton.
    - Cyprina? sp.
9835. Sec. 7, T. 25 N., R. 26 E. From shale above thin-bedded limestone which overlies the Madison limestone:
    - Dosinia? sp. undet.
    - Eumicrotis curta Hall.
    - Ostrea strigilecula White.
    - Belemnites densus Meek and Hayden.
    - Weathered casts of undetermined pelecypods.
    - Small ammonite distinct from described forms but evidently a cardioceratid.

These fossils are Upper Jurassic. Most of the species are known in the Sundance and Ellis formations, but several ammonites and a *Rhynchonella* are unlike any known Sundance forms.

The detail of part of the Ellis formation which has been identified paleontologically is as follows:

Section of Ellis formation.

	Feet.
Shale with interbedded sandstone and limestone	100±
Limestone, thin bedded, shaly, and calcareous shale	200
	300±

Above the shaly portion there is a more or less massive sandstone, which is tentatively considered as also belonging to the Ellis, though no fossils were found in it. It presents the following character in sec. 7, T. 25 N., R. 26 E.:

Section of the sandstone in the upper part of the Ellis formation.

	Feet.
Sandstone, massive, white, cross-bedded	50
Shale, variegated	50
Sandstone, yellowish, and thinner bedded	100
	200

The formation is almost identical with the Sundance formation of the Black Hills and the Ellis of other parts of Montana. As the Madison limestone is of Mississippian age, there is necessarily an unconformity between it and the Ellis (Upper Jurassic), but the actual contact of the two formations has not been recognized. A photograph (Pl. II, *C*) taken in the flanks of the Little Rocky Mountains in sec. 23, T. 25 N., R. 25 E., shows the camp situated on the outcrop of the Ellis formation in the foreground and the outcrops of the older formations in the background.

CRETACEOUS SYSTEM.

KOOTENAI (?) FORMATION.

The sandstone just described is overlain in the Little Rocky Mountain section by variegated shale interbedded with yellow and brown sandstones, which are believed to represent the Kootenai formation (Lower Cretaceous) of other parts of Montana, though they may possibly include the Morrison. The shale is in places blue, green, red, and gray. The approximate thickness, as determined by only one measurement, is 825 feet. From 100 to 200 feet above the massive sandstone there is an exposure of carbonaceous sandstone and sandy shale containing woody fragments and impressions of poorly preserved stems which may represent the coal beds occurring in the Kootenai in the neighborhood of Great Falls or the corresponding Lakota of the Black Hills. No fossils were found in this part of the section during the season of 1916, but Weed and Pirsson report that it contains *Goniabasis sublaevis* Meek and Hayden, *Corbicula cytheriformis* Meek and Hayden, and an *Ostrea*.

COLORADO GROUP.

MOWRY SHALE.

Above the Kootenai (?) formation is a well-marked siliceous shale (fig. 2) which has been recognized at several localities and is the highest formation described by Weed and Pirsson in their paper on the geology of the Little

Rocky Mountains. When freshly broken it is brown or black, but on weathering it becomes light colored and breaks into porcelain-like débris. It contains numerous fish scales and bones, some of which can be found on nearly every piece examined, and on some specimens the trails of small marine animals, probably crustaceans, were also found. Thin sections under the microscope show that the material of this shale consists of small, angular grains of quartz interbedded with a dark amorphous substance, probably carbon. Two distinct forms of Infusoria were seen, but their nature could not be determined in the material at hand. In appearance this shale resembles the shale of the Green River formation (Eocene) in Colorado and Utah, from which oil may be obtained by distillation, but a small fragment tested by distillation yielded only a trace of oil. On the basis of its lithologic similarity and content of fish scales, this shale is correlated with the Mowry shale, which occurs at several localities in Wyoming and southern Montana. Around the Little Rocky Mountains its outcrop is marked by a low ridge covered with pines. The thickness of the formation is about 100 feet.

COLORADO GROUP ABOVE THE MOWRY SHALE.

Above the Mowry shale, in the region surrounding the Little Rocky Mountains, there is about 325 feet of dark-blue shale which differs slightly in color from the dark-gray gumbo shale higher in the section. The exposures are not continuous, and little can be said of the details of this part of the section.

This shale is overlain by a sandstone capped by a foot or more of impure limestone containing fossil gastropods and pelecypods which have been identified by T. W. Stanton as of Benton age. J. B. Reeside, jr., who examined the collection, reports the following species: *Callista orbiculata* Hall and Meek, *Pachymelania?* sp. undescribed, *Amauropsis?* sp. undescribed. The stratigraphic position of this sandstone is not far from that of the Frontier formation of Wyoming and southern Montana. Its thickness could only be estimated and is given in the table as about 60 feet.

The sandstone noted above is overlain by about 875 feet of bluish-gray to black shale, much of which is concealed and in which sandy facies if present were not recognized. The only fossils found in it were baculites, a few of which, collected from limy concretions, were submitted to J. B. Reeside, jr., who reports upon them as follows:

> *Baculites* sp., usually referred to *B. asper* Morton. It is quite distinct from the related Pierre *B. asper* and from *B. anceps obtusus*. It has been collected from several localities in the Benton of Montana. (Collection 9841.)

MONTANA GROUP.

EAGLE (?) SANDSTONE.

The sandstone that lies above the shale just described in the region surrounding the Little Rocky Mountains is marked by a ridge about 30 feet high (fig. 2), the top of which is covered with large limestone concretions resting on sandstone. One poorly preserved specimen of *Nemodon*, referable to an undescribed species from the Claggett near Havre, was found (collection 9842). The same formation was seen at a locality about 3 miles southeast of the point where the section was measured, and although it was not closely studied it was thought to be about 100 feet thick. This sandstone is about 750 feet below the base of the Judith River formation, and if it is the Eagle sandstone it proves that the overlying formation varies a great deal in thickness, for the Eagle sandstone is described by Stebinger[1] as being from 350 to 500 feet below the base of the Judith River formation. Reports of drilling northeast of Malta, in the Bowdoin dome, seem to indicate that the Eagle sandstone is not present there as a mappable unit.

CLAGGETT SHALE.

The Claggett shale represents part of a marine formation called the Pierre shale in regions to the east and southeast, which to the west is represented by four formations—the Eagle sandstone, Claggett shale, Judith River formation, and Bearpaw shale. Of these formations the Judith River is of fresh-water origin. The Claggett shale on the east side of the Little Rocky Mountains, where its top and bottom are exposed, measures approximately 750 feet. In the center of the Bowdoin dome north of Saco about 500 feet of the upper part of the formation is exposed. Stebinger, working in the vicinity of Havre, about 90 miles to the west, reports the thickness of this formation as from 350 to 500 feet. It consists of a dark-gray shale which on weathering forms typical gumbo soil. Scattered through the formation in many places are concretions or masses of impure limestone, many of which contain marine fossils, or of aragonite, a mineral resembling fossil wood. The formation also contains large flakes of selenite or transparent gypsum, and water in wells, springs, or small streams in the area of its outcrop is always more or less alkaline. This shale forms the lower slopes of the valley of Milk River between Hinsdale and Malta. Two collections of fossils from it were referred to J. B. Reeside, jr., who identified one species, *Baculites compressus* Say, regarded as characteristic of the Pierre shale.

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[1] Stebinger, Eugene, Possibilities of oil and gas in north-central Montana: U. S. Geol. Survey Bull. 641, p. 53, 1917.

About 70 feet of strata in the upper part of the Claggett shale appear to form a transition zone between the Claggett and the Judith River formation. This zone is found on the west side of the Bowdoin dome, north of Malta. On the north side of the dome, near Whitewater post office, it does not contain the characteristic sandstone, and it can not be recognized at all on the east side near Hinsdale. The following sections will illustrate this peculiarity:

Sections of the transition zone of the Claggett and Judith River formations.

West of the Bowdoin dome near the center of T. 31 N., R. 30 E.

	Feet.
Typical Judith River formation.	
Shale resembling the Claggett	50±
Sandstone resembling Judith River formation containing abundant marine fossils	20±
Typical Claggett formation.	
	70±

North of the Bowdoin dome in Tps. 34 and 35 N., R. 32 E.

Typical Judith River formation.	
Shale containing fossils similar to those of the marine sandstone of the preceding section	50±
Typical Claggett shale.	

The following lots of fossils collected from the upper part of the Claggett shale have been identified by Mr. Reeside, who finds that they are marine forms characteristic of the Pierre shale.

10016. Sec. 32, T. 35 N., R. 32 E.:
  Lunatia subcrassa Meek and Hayden.
10017. Sec. 25, T. 33 N., R. 30 E.:
  Tancredia americana Meek and Hayden (fragments).
  Lunatia subcrassa Meek and Hayden.
9829. North half of T. 31 N., R. 30 E.:
  Cardium speciosum Meek and Hayden.
  Tancredia americana Meek and Hayden.
  Lunatia subcrassa Meek and Hayden.
  Haminea subcylindrica Meek and Hayden.
9830. Western part of T. 31 N., R. 30 E., south of Assinniboine Creek:
  Anatina sp. undescribed.
  Mactra alta Meek and Hayden.
  Tancredia americana Meek and Hayden.
  Cardium speciosum Meek and Hayden.
  Anchuria sp. undet.
  Lunatia subcrassa Meek and Hayden.
  Placenticeras intercalare Meek.
  Baculites compressus Say.

JUDITH RIVER FORMATION.

Above the Claggett shale lies the Judith River formation, estimated from several imperfect measurements to range from 400 to 425 feet in thickness. The outcrop of this formation surrounds the Bowdoin dome, standing out as a light-colored formation in the hill south of the railroad from Malta to Vandalia and north of the railroad near Valleytown and Lovejoy. It also crops out in one of the surrounding sandstone ridges of the Little Rocky Mountains. It probably extends east of the Bowdoin dome beneath the surface, at least as far as the mouth of Milk River, where it has probably been reached in an artesian well at a depth of 750 feet. To the southeast the Judith River formation is not recognizable as a distinct unit, as shown by the gas wells sunk on the Glendive anticline. A characteristic view of the Judith River formation is given in Plate III, *A*. The formation consists of extremely variable beds of hard brown sandstone, soft, friable light-colored sandstone, and light-gray shale; and on account of their variability no beds were found that would serve as horizon markers. In describing this formation Stanton and Hatcher[1] say:

> A detailed section taken at any point is of little value, since a similar section made at a distance of only a mile or two would give a quite different sequence of the alternating strata of sandstones and shales.

Some of the details of this formation may be seen from two sections which were measured in its upper part on the east side of Rock Creek, as follows:

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[1] Stanton, T. W., and Hatcher, J. B., Geology and paleontology of the Judith River beds: U. S. Geol. Survey Bull. 257, p. 34, 1905.

Sections of part of the Judith River formation.

On east canyon wall of Rock Creek, in sec. 20, T. 34 N., R. 36 E.

	Feet.
Bearpaw shale above Judith River formation.	
Sandstone, massive, grayish, with iron concretions scattered or in beds; weathers yellowish; some red bands cross-bedded	32
Shale, brown, in places approaching lignite	2
Sandstone, soft, yellowish gray, and gray shale	23
Lignite	½
Shale, brown	1
Shale, gray	4
Shale, dark, carbonaceous	½
Shale, gray, and sandstone	5
Lignite	⅓
Shale, brown	⅔
Shale, gray	6
Shale, brown	3
Sanstone, soft, with iron concretions	1
Shale, sandy, brown	2
Sandstone, soft, gray	6
Clay, shale gray	4
Shale, brown	3
Sandstone, soft, gray, and sandy shale	9
Sandstone, concretion bed	1
Shale, soft, sandy, gray	5
Sandstone, iron-concretion bed	1
Shale, blue and gray	4
Concretions	1
Shale, gray	4
Shale, brown	2
Sandstone, soft, gray and yellow	17
Sandstone, massive; weathers brown; arkosic, containing much feldspathic and ferromagnesian material. This bed forms conspicuous ledges	7
Sandstone, soft, gray; some shale	20
Base of formation not exposed.	
	165

East canyon wall of Rock Creek, near line between sec. 32, T. 34 N., R. 36 E., and sec. 4, T. 33 N., R. 36 E.

	Feet.
Glacial gravel.	
Sandstone, massive, gray; weathers yellow or reddish; some thin beds; cross-bedded	47
Shale, gray	6
Sandstone, soft, gray	2
Shale, gray	4
Shale, brown	3
Shale, gray	2
Shale, brown	1
Sandstone, soft, gray	5
Shale, brown, with 3 inches of lignite	2
Shale, gray	5
Shale, brown	6
Shale, blue	2
Sandstone, soft	9
Shale, brown	1½
Sandstone, soft, gray	3
Shale, blue-gray	5
Concretions	6
Sandstone, soft, massive, gray	18
Shale, brown	⅔
Lignite	⅓
Shale, brown	5
Shale, blue-gray	12
Shale, brown	1
Shale, sandy	6
Sandstone, concretions	1
Shale, gray	10
Sandstone, soft, gray	13
Shale, dark	3
Sandstone, soft, gray, and sandy shale	14
Shale, brown	2
Sandstone, massive, soft, gray or yellowish, weathering yellowish; certain beds weather out as massive reddish layers or as huge concretions; shows some cross-bedding	101±
Base of formation not exposed.	
	296±

The base of this formation is not very definitely marked and can not everywhere be separated from the upper part of the Claggett shale, but its top can be readily recognized in the few places where it is well exposed. The upper part of the Judith River formation consists of a massive sandstone in the two sections cited and in the neighborhood of the Little Rocky Mountains, and is overlain by characteristic Bearpaw shale. At other places in the region the massive sandstone is not prominent, and in one or two localities a small bed of lignite within a few feet of the top has been mined. Stanton and Hatcher report a layer of shell breccia consisting of shells of *Ostrea subtrigonalis* near the top of the Judith River formation as its most persistent horizon marker, but such beds were not seen in the neighborhood of the Bowdoin dome. Invertebrate fossils collected from the formation during the season of 1916 have been examined by Mr. Reeside, who reports that six lots consist of marine forms and one lot from the flanks of the Little Rocky Mountains contains fresh-water forms of Judith River types. The species identified are as follows:

9826. Sec. 36, T. 33 N., R. 37 E., on road:
    Plates of an undescribed barnacle.
    Tancredia americana Meek and Hayden.
    Cardium speciosum Meek and Hayden.
    Protocardia sp.?, large form.
    Mactra sp.?
    Inoceramus sp.?, very young individual.
    Nucula sp.?
    Lunatia subcrassa Meek and Hayden.

9826. Sec. 36, T. 33 N., R. 37 E., on road—Continued.
Cf. Trachytriton vinculum Meek and Hayden.
Scaphites sp., fragment suggesting S. nicolleti Morton.
Baculites sp.?, fragment.

Most of this lot consists of casts lacking essential details. The *Protocardia?*, *Lunatia*, and *Scaphites* suggest Bearpaw rather than typical Judith River.

9843. SW. ¼ sec. 21, T. 33 N., R. 37 E., on Eagle Creek; upper part of Judith River formation:
Liopistha undata Meek and Hayden.
Pteria nebrascana Edwards and Solander.
Marine; Pierre fauna.

41. Sec. 4, T. 33 N., R. 37 E., on Bitter Creek; upper part of Judith River formation:
Natica sp.?
Mactra sp.?
Serpula sp.?

The only fresh-water forms are found in the following lot:

9837. Sec. 21, T. 25 N., R. 26 E., sandstone about middle of Judith River formation at east end of Little Rocky Mountains:
Unio cf. U. primaevus White.
Unio cf. U. supragibbosus Whiteaves.

This lot consists of fragments which suggest a reference to the Judith River but are too poor to be conclusive. *Unio supragibbosus* occurs in the Canadian Belly River and in the Judith River formation. *U. primaevus* is a Judith River species.

Inasmuch as this lot of fresh-water forms is from the middle of the formation, while the majority of the fossils found are marine, it is probable that the Judith River formation of this area is marine at the top and bottom.

Bones of fresh-water dinosaurs were collected at several localities and were examined by C. W. Gilmore, of the National Museum, who found them too fragmentary for specific determination.

Specimens of petrified wood, described by F. H. Knowlton as that of cone-bearing trees, were collected at several places in the Judith River formation, but no determinable fossil leaves were found.

This formation contains small lenticular beds of lignite or subbituminous coal which are too thin to be of value. Local mines from which the farmers have obtained a small amount of fuel were examined at the points where the following sections were measured:

Sections of Judith River formation in northeastern Montana.

Location.			Section.		
Sec.	T. N.	R. E.		Ft.	in.
21	33	37	Bearpaw shale.		
			Sandstone	20±	
			Lignite		8
			Sandstone and shale	15±	
			Shale, carbonaceous, and lignite	2±	
4	33	37	Bearpaw shale.		
			Sandstone and shale	59	0
			Lignite		6
			Sandstone and shale	22	0
			Shale, carbonaceous	2	0
			Lignite		8
			Shale, carbonaceous	2	0
5	33	37	Shale, blue	4	6
			Shale, carbonaceous		6
			Lignite	1	2
			Shale, carbonaceous		6
15	32	37	Sandstone	10	0
			Lignite	1	4
			Shale, sandy gray	3	0
16	32	37	Lignite, a few inches.		
7	34	36	Shale, gray	5	0
			Lignite	1	4
			Shale, brown	1	0
12	34	35	Lignite		6
32	34	35	Shale, gray	5	0
			Shale, brown		2
			Lignite		8
			Shale, brown		4
			Shale, gray.		
6	33	35	Shale, gray	5	0
			Lignite		10
			Shale, brown		8
			Shale, gray.		
20	34	34	Shale	10	0
			Lignite		6
			Shale, brown.		
			Shale, gray	1+	
5	35	34	Lignite		6
9	35	34	Lignite		8
9	28	32	Lignite		6–10
9	28	34	Bearpaw shale.		
			Judith River formation	50±	
			Clay, black, carbonaceous	1	6
			Lignite		10

BEARPAW SHALE.

The Bearpaw shale, from 800 to 1,000 feet thick is, as shown on Plate I, the most widespread formation exposed in the region described, and overlies the Judith River formation. It consists essentially of dark-gray shale which forms a gumbo soil and presents an uninteresting and monotonous landscape. This shale is exposed in many places along escarpments and canyons and forms badlands which lack the variety due to the presence of harder beds. A characteristic view of the badlands of the Bearpaw shale is given in Plate III, *B*. The fossils are all of marine types; *Baculites, Inoceramus,* and oysters are very abundant, and occasionally the remains of a gigantic marine saurian are found. The formation in places contains limy concretions, in which the lime is in the form of aragonite showing cone in cone structure or appearing like the stumps of large trees. Calcite also is present in many of these concretions, and smaller masses of barite were noted in several localities. The formation contains more or less gypsum, which at some places is transparent and at others occurs in uncrystallized forms replacing the calcite of oyster shells. The water from the Bearpaw shale, like that from the Claggett, is usually alkaline.

The following invertebrate fossils were collected during the field season of 1916 and were identified by J. B. Reeside, jr.:

9825. SW. ¼ sec. 22, T. 33 N., R. 37 E.:
Inoceramus sagensis Owen.
Heteroceras sp. related to H. newtoni Meek but probably undescribed.
Pierre fauna; fossils not distinctive of Bearpaw shale.

9827. Sec. 36, T. 36 N., R. 36 E.:
Ostrea patina Meek and Hayden.
So far as known this form is confined to the Bearpaw shale.

9828. Sec. 5, T. 36 N., R. 26 E.:
Chlamys nebrascensis Meek and Hayden.
Baculites compressus Say.
Cf. Trachytriton vinculum Say.
Membranipora sp. undescribed (identified by R. S. Bassler).
Pierre fauna.

9838. Sec. 21, T. 25 N., R. 26 E.:
Ostrea patina White

9839. Sec. 21, T. 25 N., R. 26 E.:
Inoceramus sagensis Owen.
Baculites sp., fragments.
Pierre fauna.

10020. Sec. 10, T. 23 N., R. 36 E., 150 to 200 feet below top of Bearpaw shale:
Scaphites nodosus var. plenus Meek.
Baculites compressus Say.
Cyprimeria? sp., single weathered individual.
Pierre fauna.

10021. Southwestern part of T. 23 N., R. 36 E., 50 to 100 feet below top of Bearpaw shale:
Baculites compressus Say.
Pierre fauna.

10024. Northeastern part of T. 23 N., R. 34 E., 50 feet below top of Bearpaw shale, on Timber Creek:
Baculites compressus Say.
Pierre fauna.

10025. T. 26 N., R. 34 E., along Larb Creek; middle of Bearpaw shale:
Baculites sp., fragments.
Pierre fauna.

10028. T. 24 N., R. 41 E., near top of Bearpaw shale:
Inoceramus sagensis Owen.
Protocardia subquadrata Edwards and Solander.
Anomia sp., fragments.
Yoldia evansi Meek and Hayden.
Lunatia sp., fragments.
Dentalium gracile Meek and Hayden.
Anchura sp., fragment.
Actaeon attenuatus Meek and Hayden.
Scaphites sp., probably young S. nodosus plenus Meek.
Bearpaw shale.

Parts of skeletons of two large marine reptiles collected in this region, one found several years ago by Ira Taylor, were submitted to C. W. Gilmore, who identified one of them (from sec. 23, T. 37 N., R. 35 E.) as consisting of numerous parts of vertebrae, limb bones, fragmentary teeth, jaws, and other fragments of a large plesiosaurian reptile; and the other (from sec. 23, T. 34 N., R. 38 E.) as consisting of numerous vertebrae and other parts of the skeleton of a mososaurian reptile. Neither of these forms was otherwise determinable. The remains of both animals are found only in marine or brackish-water formations

TERTIARY (?) SYSTEM.

LANCE FORMATION.

The Lance formation, which overlies the Bearpaw shale, as here identified, is composed of two more or less distinct members in the eastern and southern parts of the region described. In the northwestern part, in the Cherry Ridge quadrangle, the exposures are too meager to indicate their character.

The lower member has been described by Dawson,[1] who estimated the thickness at 80 feet and referred it to the Fox Hills sandstone. Figure 4, reproduced from Dawson's report, shows the relation of the two members near the international boundary northwest of Opheim. The lower member is here composed of yellowish and rusty sands grading into arenaceous clay toward its base. It is characterized by large, irregular sandy concretions which in places approach a more or less spherical form and are slightly darker than the prevailing color of the formation. So far as the writer knows marine fossils have not been obtained from this member within the region described. Rose,[2] in his description of beds he designated Fox Hills sandstone in the Wood Mountain district of Canada, gives a list of the fossils found by R. G. McConnell in beds designated Pierre and Fox Hills formations in the Cypress Hills, but as no effort is made to distinguish between the formations the list is probably of little value.

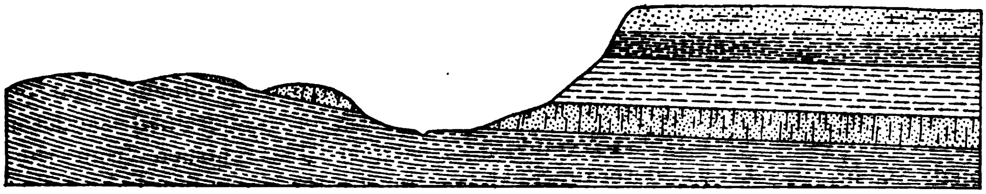

FIGURE 4.—Section in badlands south of Wood Mountain, Saskatchewan, Canada, showing the relation of Fort Union formation (*a*), upper part of Lance formation (*b*), lower part of Lance formation (*c*), and Bearpaw shale (*d*).

A very good exposure of yellowish sandstone, resembling that at the boundary, covers 2 or 3 square miles in and around sec. 34, T. 36 N., R. 39 E. In this sandstone, which surely lies only a short distance above the Bearpaw shale, was found a well-preserved fossil bone which Gilmore identified as "the proximal half of the left ischium of a trachodont dinosaur. So far as it can be compared it appears identical with the same element in *Trachodon annectens* Marsh, from the Lance formation." The finding of this fossil justifies the belief that the lower part of the Lance is a fresh-water deposit and should not be classified as the Fox Hills sandstone, which in the type locality is marine. It may, however, be contemporaneous with the Fox Hills sandstone of South Dakota. Small exposures of this member are found in T. 37 N., R. 40 E., and T. 35 N., R. 44 E., where it is similar in lithologic character to the rocks northeast of Opheim.

In the Larb Hills, in the southern part of the region described, a similar member having a thickness of about 100 feet where measured in sec. 13, T. 24 N., R. 32 E., rests upon the Bearpaw shale and is capped by a harder sandstone. The same succession of beds is exposed south of Missouri River, where Brown[3] reports collecting 14 species of marine invertebrate fossils, identified as the Fox Hills fauna, from concretions found on Hell Creek. He further reports[4] that in the same valley, 20 feet below the base of the sandstone he calls Fox Hills, the remains of a large trachodont dinosaur were discovered. The specimen was found in place partly embedded in a large calcareous concretion that was weathered out and broken. The humeri were still covered with shale and well preserved.

This member northwest of Opheim is probably the same as that found on Missouri River in the southeastern part of the region here described and called the Fox Hills sandstone by Smith.[5] (See Pl. IV, *A*.) It is described in a later report by Beekly[6] as the Colgate sandstone member of the Lance formation, consisting of 50 to 150 feet of buff sandstone interstratified with somber-colored and yellow clay. The type locality is the vicinity of Colgate station on the Northern Pacific Railway, described by Calvert.[7]

The upper member of the Lance formation is composed of shale and argillaceous sandstone and is characteristically of somber color. Its thickness is from 180 feet northwest of Opheim to 250 feet where measured in the Larb Hills. At some places the argillaceous sandstone shows cross-bedding, due to wind action while it was being deposited (Pl. IV, *B*). Its erosion results in many picturesque badlands or isolated pinnacles capped by hard concretions (Pl. V, *A*) or interesting corrugated forms resembling organ pipes (Pl. V, *B*). The Lance formation in many places contains loglike sandstone concretions and carries near its top one or more somewhat irregular lignite beds. The bed mined northeast of Opheim has a maximum thickness of about 6 feet; that near Daleview is over 12 feet thick and extends with varying thickness throughout the outcrop of the Lance formation on Big Muddy Creek. In other parts of the region there are lignite beds too thin to be of commercial value.

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[1] Dawson, G. M., Geology of the 49th parallel, British North American Boundary Commission, Montreal, 1875.

[2] Rose, Bruce, Wood Mountain-Willowbunch coal areas, Saskatchewan: Canada Geol. Survey Mem. 89, p. 32, 1916.

[3] Brown, Barnum, The Hell Creek beds of Montana: Am. Mus. Nat. Hist. Bull. 23, p. 827, 1907.

[4] Idem, p. 826.

[5] Smith, C. D., The Fort Peck Indian Reservation lignite field, Mont.: U. S. Geol. Survey Bull. 381, p. 42, 1908.

[6] Beekly, A. L., The Culbertson lignite field, Valley County, Mont.: U. S. Geol. Survey Bull. 471, pp. 329, 330, 1912.

[7] Calvert, W. R., Geology of certain lignite fields in eastern Montana: U. S. Geol. Survey Bull. 471, pp. 194, 195, 1912.

Brown[1] has described numerous fossil vertebrates, mostly dinosaurs, the most striking of which is the large three-horned *Triceratops*, which he collected from the south side of Missouri River opposite the Larb Hills. Fragments of dinosaur bones collected in 1916 from the Lance formation in the Larb Hills were not good enough to be specifically determined. C. W. Gilmore reports that a small collection made northwest of Opheim in sec. 23, T. 37 N., R. 39 E., consists of

> foot bones, vertebra, chevrons, etc., of *Thescelosaurus neglectus* Gilmore; caudal vertebra of a carnivorous dinosaur, not determinable; two fragments of a turtle shell, probably pertaining to the genus *Aspidontes*. The presence of *Thescelosaurus neglectus* would indicate that these fossils came from the Lance formation, for the four or five specimens of the genus known at this time are all from the Lance.

A single vertebra collected near the top of the Lance formation in sec. 27, T. 37 N., R. 46 E., is that of *Champosaurus* sp., characteristic of both the Lance and Fort Union formations.

Several small collections of invertebrate fossils, made in the Larb Hills, have been identified by Mr. Reeside as follows:

10022. Sec. 29, T. 24 N., R. 35 E.
    Unio brachyopisthus.
    Unio holmesianus.
10023. Sec. 29, T. 24 N., R. 35 E.
    Unio cf. U. brachyopisthus White.
    Sphaerium subellipticum Meek and Hayden.
    Viviparus sp., fragment.
10026. Sec. 29, T. 24 N., R. 35 E.
    Tulotoma thompsoni White.
10027. Sec. 25, T. 25 N., R. 34 E.
    Sphaerium subellipticum Meek and Hayden.
    Campeloma multilineata Meek and Hayden.

All are probably from the Lance formation.

Fossil wood from the Lance formation has been identified by Knowlton as that of coniferous trees, but no identifiable fossil plants were collected.

TERTIARY SYSTEM.

FORT UNION FORMATION.

Overlying the somber-colored shale of the Lance formation is the Fort Union formation, of Eocene age, which is exposed along the North Dakota line and extends more or less continuously westward as far as Opheim. It carries the principal lignite beds of the region and also contains widely distributed beds of clay and shale[2] suitable for the manufacture of brick and other clay products. The formation is composed of fine-grained sandstone and shale and is distinguished from the Lance formation by the prevailing light-yellow color. Like the Lance formation, it has, especially in its lower part, concretions of hard sandstone resembling fossil logs. (See Pl. VI, *C*.) Observations made along the contact of the Lance and Fort Union formations indicate that the change in color is not always noticeable at exactly the same horizon. The mapping of the contact of these formations on Plate I is based on the judgment of the geologists making the examination in each locality. According to Beekly[3] the thickness of the Fort Union remaining at the southeast end of the region mapped is about 1,400 feet. The lower part is probably equivalent to the Lebo shale member of the Fort Union, described by Rogers.[4] The following section of the Lance and Fort

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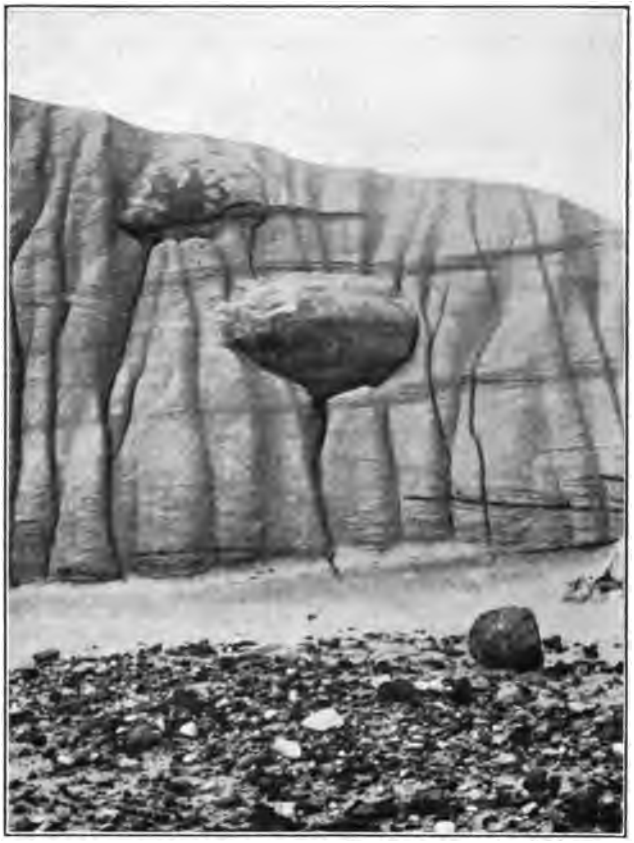
[1] Brown, Barnum, op. cit., pp. 823-845.

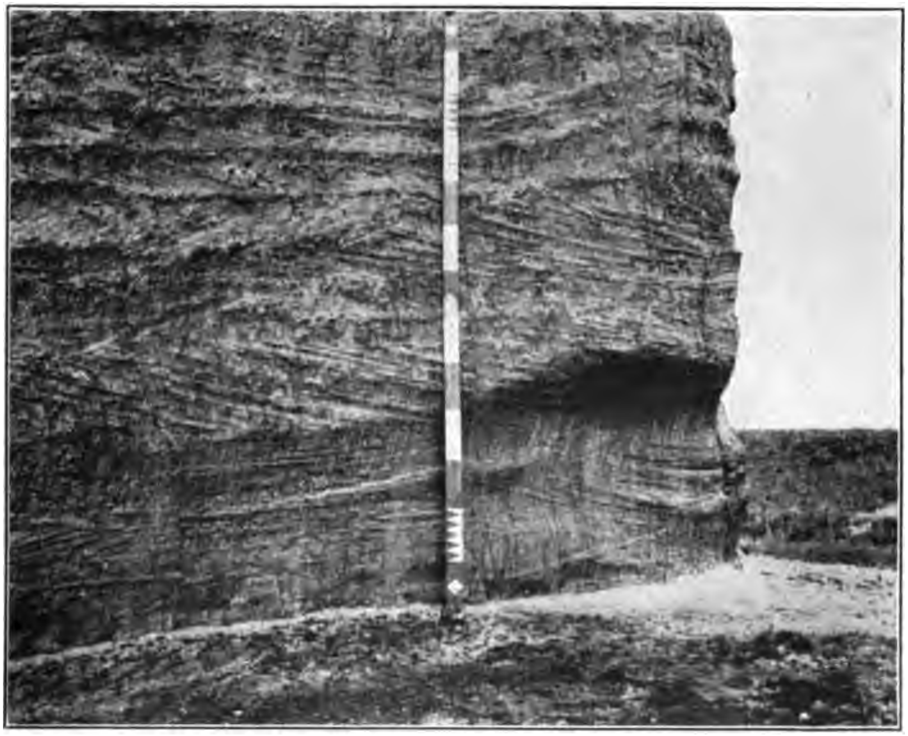
[2] Rose, Bruce, Wood Mountain-Willowbunch coal areas, Saskatchewan: Canada Geol. Survey Mem. 89, pp. 69-83, 1916. Bauer, C. M., Clay in northeastern Montana: U. S. Geol. Survey Bull. 540, pp. 369-372, 1914.

[3] Beekly, A. L., The Culbertson lignite field, Valley County, Mont.: U. S. Geol. Survey Bull. 471, pp. 326, 331, 1912.

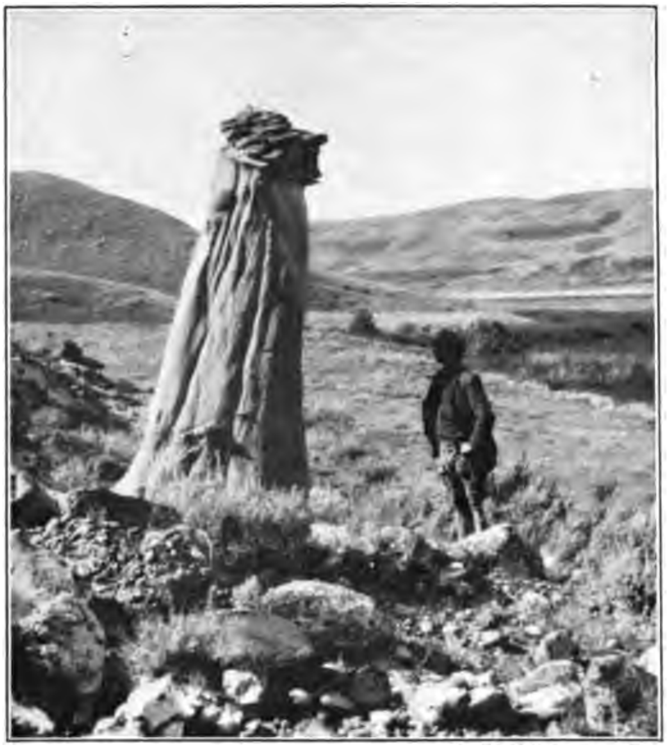
[4] Rogers, G. S., The Little Sheep Mountain coal field, Dawson, Custer, and Rosebud counties, Mont.: U. S. Geol. Survey Bull. 531, pp. 12, 13, 1913.



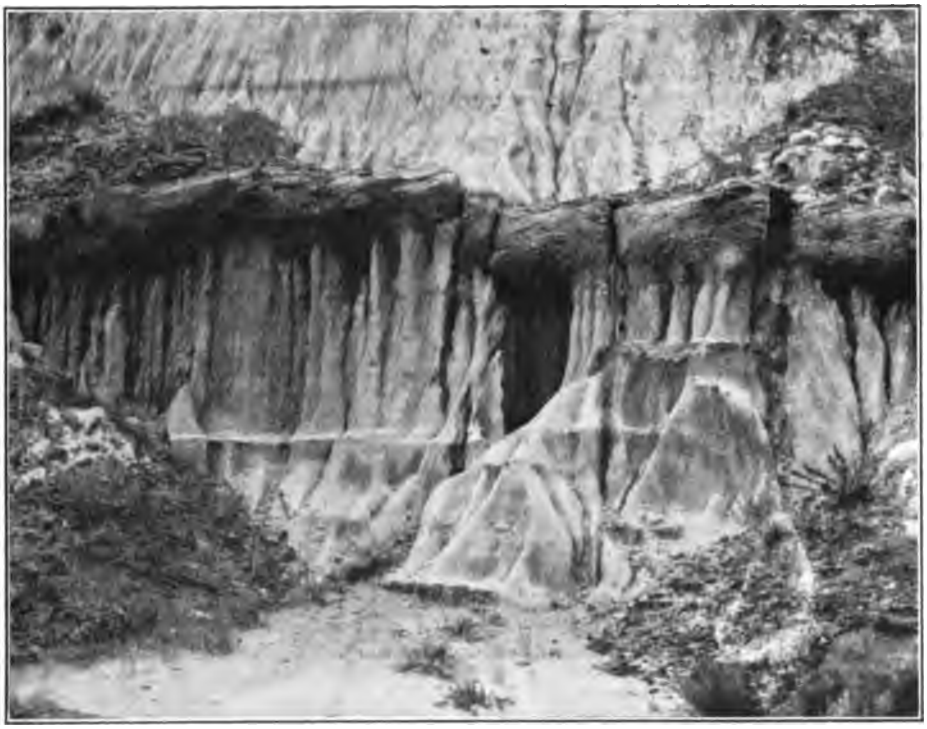
A. LOWER PART OF THE LANCE FORMATION, SHOWING SPHERICAL CONCRETIONS.



B. ARENACEOUS SANDSTONE, SHOWING EOLIAN CROSS-BEDDING.



A. PINNACLE OF SOFT SANDSTONE OF LANCE FORMATION.



B. EROSION FORM OF LANCE FORMATION.

Union formations exposed from Redstone to Plentywood (Pl. I) is much generalized:

Generalized section of the Lance and Fort Union formations between Redstone and Plentywood, Mont.

	Ft.	in.
Fort Union formation:		
Sandstone and shale	81	0
Lignite		6
Sandstone and shale	67	0
Shale	52	0
Lignite, Richardson bed	6±	
Sandstone and shale more or less concealed	320±	
Lignite, upper Eagles Nest bed	6	3
Shale and sandstone, yellowish	50±	
Lignite, lower Eagles Nest bed	4	0
Shale and sandstone, yellowish	70	0
Lignite		10
Shale and sandstone, yellowish	19	0
Lignite	1	2
Shale and sandstone, yellowish	18	0
Lignite		4
Shale, grading upward into sandstone, yellowish	20	0
Lignite	1	6
Shale and sandstone, yellowish	60±	
Lignite, Redstone bed	6	0
Shale and sandstone, yellowish	22	0
Lignite	2	0
Lance formation:		
Shale and sandstone, somber color	30	0
Lignite	1	10
Shale and sandstone, somber color	27	0
Lignite	6	0
	872±	

The following generalized section of the Fort Union and its lignite beds as exposed on Missouri River in the southeastern part of the region is taken from Beekly's report:[1]

Generalized section showing the distribution of lignite beds in the Fort Union formation.

Culbertson field, 2 miles east of Lakeside.

	Ft.	in.
Clay and shale	125	0
Lignite, bed H	4	0
Clay and shale	70	0
Lignite, bed G	4	0
Clay and sandy shale	150	0
Lignite	1	10
Sandstone and clay	30	0
Lignite	1	2
Sandstone and shale	55	0
	441	0

Culbertson field, sec. 3, T. 27 N., R. 56 E.

	Ft.	in.
Lignite, bed F	7	0
Sandstone and shale	45	0
Lignite, bed E	6	4
Sandstone with some shale	121	0
Lignite	1	0
Sandstone and shale	24	0
Lignite, bed DD	4	4
Sandstone and shale	70	0
Lignite, bed CC	2	5
Sandstone and clay	130	0
Lignite	5	7
	416	8

Fort Peck field west of Big Muddy Creek.

[C. D. Smith, 1908.]

	Ft.	in.
Clay	6	0
Lignite, bed D	9	0
Sandstone and clay	95	0
Lignite, bed C	2	0
Sandstone and clay	115	0
Lignite, bed B	3	0
Sandstone and clay	275	0
Lignite	5	0
Clay	15	0
Lignite, bed A	7	7
Somber-colored beds (Lance).		
	532	7
	1,390	3

The following section, measured in sec. 18, T. 24 N., R. 33 E., shows the relations of the Fort Union, Lance, and Bearpaw formations in the Larb Hills:

Section showing the relation of the Fort Union, Lance, and Bearpaw formations in the Larb Hills, Mont.

	Ft.	in.
Fort Union formation:		
Sandstone, yellowish	50	0
Lignite		3
Sandstone, soft, yellowish	20	0
Lignite	1	0
Sandstone, soft, yellowish	11	0
Lignite	1	0
Sandstone, soft, yellowish	20	0
Lignite	6	0
	109	3
Lance formation:		
Shale and sandstone, somber color	50	0
Lignite		6
Shale and sandstone, somber color; contains dinosaur bones	100	0
Concealed	100	0
Shale, sandy	100	0
Bearpaw shale.		
	350	6
	459	9

The relations of these sections are shown graphically in figure 5.

Full descriptions of the lignite beds in each township are given in other reports.[2]

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[1] Beekly, A. L., op. cit., p. 331.

[2] U. S. Geol. Survey Bull. 381, pp. 40–59, 1910; Bull. 471, pp. 319–358, 1912; Bull. 541, pp. 293–315, 1914; and a report not yet published.

The following small collections of fossil plants have been examined by F. H. Knowlton, who reports that they are of Fort Union age:

7001. Sec. 3, T. 35 N., R. 44 E.:
Sequoia nordenskioldii Heer.
Glyptostrobus ungeri Heer.
Dicotyledon, gen. and sp.?

7002. NE. ¼ sec. 31, T. 36 N., R. 45 E.:
Sequoia nordenskioldii Heer.

7004. Sec. 33, T. 37 N., R. 47 E.:
Alga.
Onoclea sensibilis fossilis Newberry.
Trapa microphylla Lesquereux of Ward.
Selaginella collieri Knowlton.[1] n. sp.
Potamogeton n. sp.

7005. Canada, near the north line of sec. 4, T. 37 N., R. 49 E.:
Onoclea sensibilis fossilis Newberry.
Taxodium occidentale Newberry.
Sequoia nordenskioldii Heer.
Platanus sp.

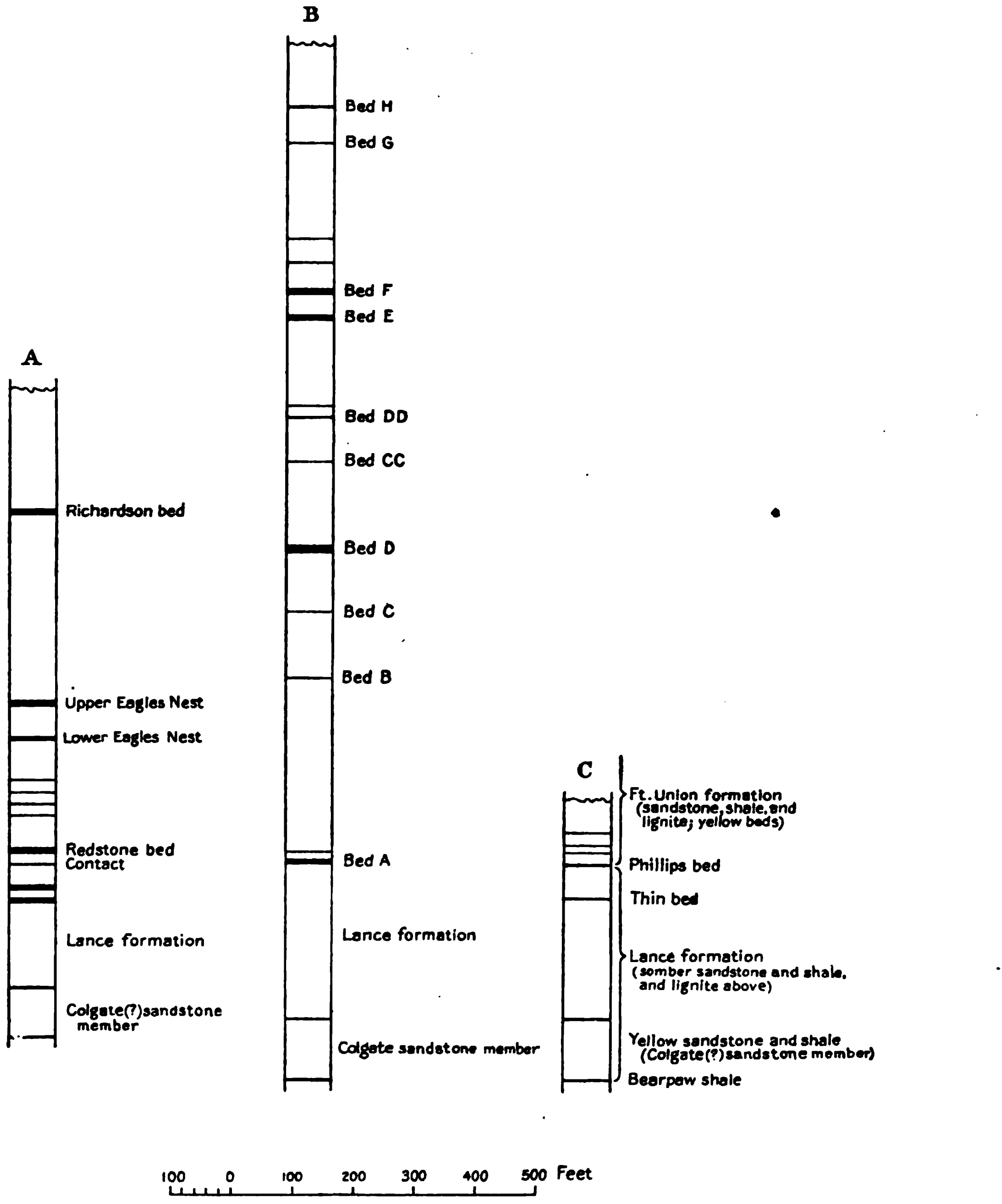
A
Richardson bed
Upper Eagles Nest
Lower Eagles Nest
Redstone bed
Contact
Lance formation
Colgate(?)sandstone member
B
Bed H
Bed G
Bed F
Bed E
Bed DD
Bed CC
Bed D
Bed C
Bed B
Bed A
Lance formation
Colgate sandstone member
C
Ft. Union formation (sandstone, shale, and lignite; yellow beds)
Phillips bed
Thin bed
Lance formation (somber sandstone and shale, and lignite above)
Yellow sandstone and shale (Colgate(?)sandstone member)
Bearpaw shale
100 0 100 200 300 400 500 Feet

FIGURE 5.—Generalized sections of Fort Union and Lance formations, showing their relation to the Bearpaw shale from its outcrop northwest of Opheim to Plentywood, Mont. (A); north of Missouri River from Brockton to the Dakota line (B); and in the Larb Hills, in T. 24 N., R. 33 E. (C).

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[1] Knowlton, F. H., A new fossil *Selaginella* from the lower Tertiary of Montana: Torreya, vol. 16, pp. 101-103, 1916.

7505. Canada, near the north line of sec. 4—Continued.
  Grewia sp.
  Persea sp.
7006. SE. ¼ sec. 21, T. 36 N., R. 52 E.:
  Taxodium occidentale Newberry.
  Sequoia nordenskioldii Heer.
  Grewia pealei Ward.
7272. NE. ¼ sec. 36, T. 37 N., R. 39 E.:
  Sequoia nordenskioldii Heer.
  Glyptostrobus europaeus Unger.
  Fragments of a dicotyledon.

Collections of invertebrates, on which T. W. Stanton has reported, were made at the following localities:

9837. SW. ¼ sec. 6, T. 35 N., R. 45 E.:
  Unio sp. fragments.
  Campeloma producta White.
  Campeloma multilineata Meek and Hayden.
 Fort Union.
9380. T. 36 N., R. 46 E.:
  Viviparus sp.
 Probably Fort Union.
9381. Sec. 13, T. 34 N., R. 50 E.:
  Unio sp.
  Campeloma multilineata Meek and Hayden.
 Fort Union.

FLAXVILLE GRAVEL.

With the Fort Union the conformable series stops, and the formations representing the later history of the region are surficial deposits of rather small extent laid down during favorable intervals between great time breaks when erosion was prevalent and no sediments were deposited.

The Flaxville gravel,[1] shown in several areas along the international boundary, is a few feet to 100 feet thick and caps a series of plateaus upon eroded surfaces of the Fort Union, Lance, and Bearpaw formations at altitudes ranging from 2,600 feet at the east end to 3,200 feet at the west end of the region described, near the international boundary. It is composed of gravel, sand, clay, volcanic ash, and marl and in places is cemented with calcite. The gravel consists of pebbles derived from the quartzite and argillite of the Rocky Mountains.

Fragments of fossil vertebrates found at 25 widely distributed localities have been submitted to J. W. Gidley, who states that the beds which contained them can not be older than Miocene or younger than early Pliocene and that they are probably upper Miocene. The time break between the Fort Union formation (Eocene) and the Flaxville gravel (Miocene) is in part represented by the Oligocene deposits found on a still higher plateau in the Cypress Hills in Canada, 50 miles away.

TERTIARY OR QUATERNARY SYSTEM.

LATE PLIOCENE OR EARLY PLEISTOCENE DEPOSITS.

Below the Flaxville level there are extensive areas across which the present streams have eroded valleys from 100 to 500 feet in depth. Stratified silt and gravel are to be found in a very few places on this level, and from one of these exposures of gravel in sec. 23, T. 33 N., R. 35 E., a single fossil tooth was collected which Dr. Gidley identified as that of a horse resembling the living species. As the gravel from which it came is clearly older than the last advance of ice during the glacial epoch, the formation is regarded as of either late Pliocene or early Pleistocene age.[2]

Extensive benches slope gently away from the Little Rocky Mountains at several levels. These benches are capped with gravel containing many pebbles of limestone and porphyry derived from the neighboring mountains and are almost surely of Tertiary age, for in some places the gravel on them is overlain by glacial drift. The lowest bench is probably equivalent to the late Pliocene or early Pleistocene bench in the region north of Milk River with which it is tentatively correlated. The presence of undissolved limestone pebbles seems to forbid the assignment of these benches to an earlier period.

QUATERNARY SYSTEM.

ALLUVIUM OF PREGLACIAL RIVERS.

Since late Pliocene or early Pleistocene time streams have been at work eroding the present valleys. The effects of this erosion can be seen in the escarpments north and south of Milk River between Tampico and Malta, where at one place 300 feet of beds belonging to the Claggett and Judith River formations, capped by late Pliocene or early Pleistocene gravel, are exposed. The cutting of the river valley must have occurred early in Pleistocene time, when the valley of Milk River was occupied by a much larger river, the Missouri,[1] and along its banks and flood plains gravel, silt, and sand were deposited. Some of this material can be seen in pits northwest of Saco and north of Malta. The gravel here differs from the Flaxville gravel in that it contains numerous fragments of porphyry.

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[1] Collier, A. J., and Thom, W. T., jr., The Flaxville gravel and its relation to other high terrace gravels of the northern Great Plains: U. S. Geol. Survey Prof. Paper 108, pp. 179-184, 1917 (Prof. Paper 108-J).

[2] Idem, p. 182.

Similar deposits occur at several points in the first benches above the flood plain of the Missouri between Milk River and the North Dakota line, and are best exposed where gravel pits are operated by the Great Northern Railway. In the summer of 1917 a pit was operated at Wolf Point, where a new freight division of the railway was being installed and where the photograph reproduced in Plate VI, *B*, was taken. Wolf Point lies about 25 feet above the Missouri, and the gravel pit is in the second bench, about 20 feet higher. The section exposed is about as follows:

Section exposed in gravel pit at Wolf Point.

	Feet.
Soil, with a few scattered granite boulders on the surface	1
Glacial till, containing granite cobbles	5
Gravel, chiefly quartzite but containing fragments of sandstone, porphyry, and near the bottom shale.	13
Shale, Bearpaw.	
	19

The gravel is interstratified with lenses of sand, and the bedding planes are nearly horizontal. The gravel consists for the most part of well-rounded pebbles of quartzite, probably derived from the Flaxville gravel, but it contains some pebbles of porphyry and fragments of sandstone and of fossiliferous Bearpaw shale near the bottom. A thorough search failed to reveal any glacial material such as granite pebbles. It was evidently deposited by Missouri River in preglacial time, for it is overlain by glacial till containing many more or less angular fragments of granite. Another gravel pit 2 miles west of Brockton shows finely laminated sand. The bedding at the west end of the pit lies nearly horizontal, whereas that at the east end dips east about 70°. The surface has been eroded irregularly and is covered with glacial till to a maximum depth of about 15 feet. The bottom of this pit is about 40 feet above the present river level.

GLACIAL MORAINES AND DRIFT.

Overlying the gravel in the Milk River valley as well as the Flaxville gravel and all the higher benches described there is in many places a sprinkling of glacial boulders, among which specimens of limestone from Lake Winnipeg and of granite from the Hudson Bay region are abundant. One large limestone erratic about 20 feet long was found by W. C. Alden and the writer just north of Nelson Reservoir. At the time this glacial drift was introduced the Missouri was probably forced out of the Milk River valley and compelled to flow through a narrow valley south of the Larb Hills. When the glacial epoch was over and the ice sheet had retreated for the last time the waters that could collect in the old channel formed Milk River, which flows in a very meandering course over the old valley floor. In addition to the scattered boulders there are in the northern part of this region accumulations of glacial material in which the topography is suggestive of moraines. There are also in the southern part of the region some large areas covered by till or boulder clay.

ALLUVIUM.

Soil of various kinds, brought in since the glacial epoch, has been deposited along Milk River and other streams of the region. On the flood plains of Milk River there is usually a gumbo soil, derived from the shale of the country, which forms a sticky mud when wet. The river has brought down a small quantity of sand in some places, and where this is deposited the soil is more easily cultivated than the gumbo.

Milk River since the retreat of the ice has trenched its flood plain about 10 or 12 feet, developing intricate meanders, and back of the river there are oxbow lakes which show the extent of the flood plain.

Big Muddy Creek, in the eastern part of the region, flows in a valley cut from 100 to 300 feet below the late Pliocene or early Pleistocene bench. Its flood plain is about a mile wide and is covered with fine silt, which provides the material that doubtless suggested the name for the creek and makes it difficult to cross on account of the muddy banks. The gravel terraces, from 20 to 50 feet above the

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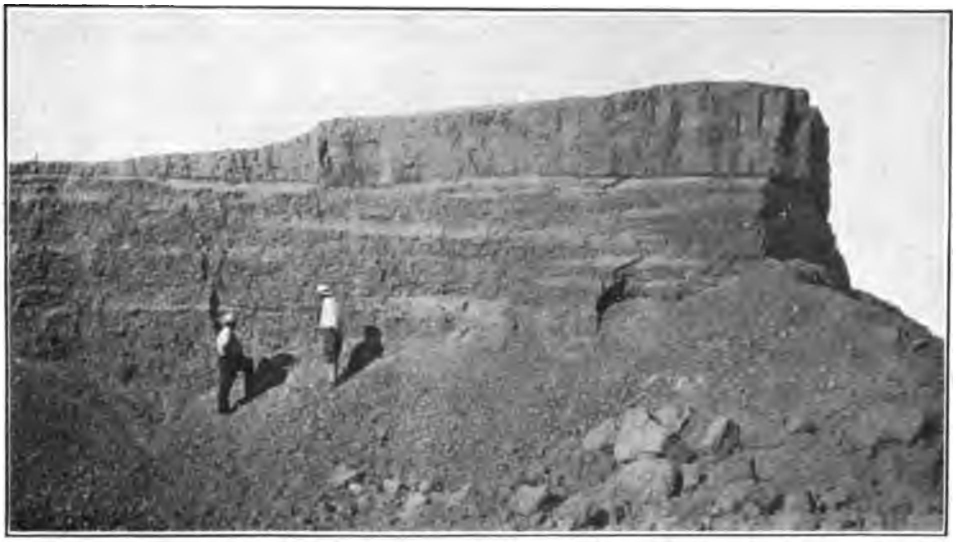
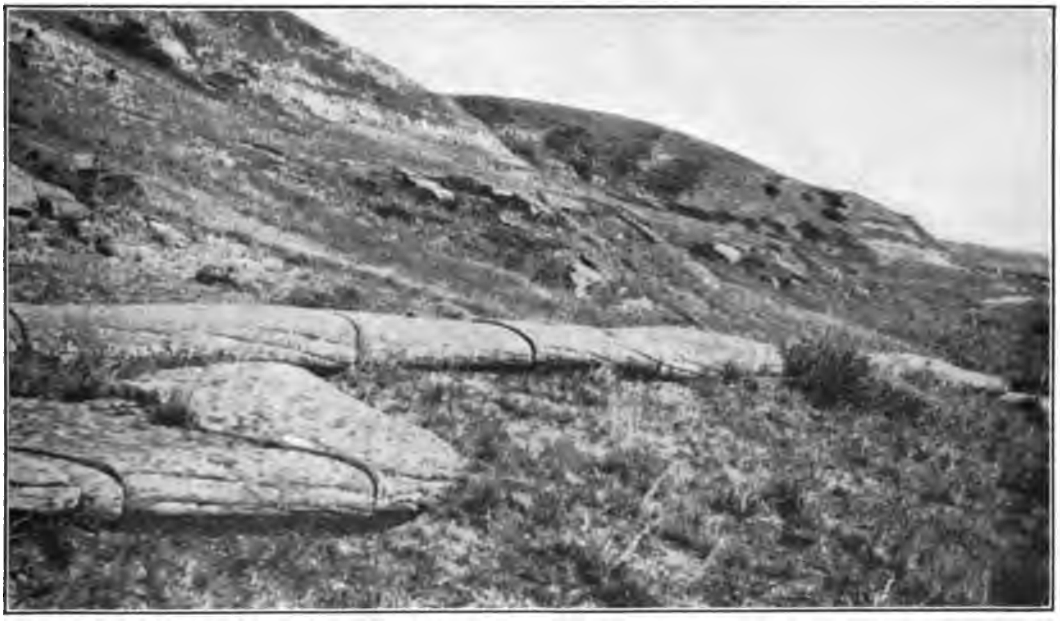
[1] Calhoun, F. H. H., The Montana lobe of the Keewatin ice sheet: U. S. Geol. Survey Prof. Paper 50, pp. 34-45, 1906.

A. VIEW SOUTH ACROSS THE MISSOURI VALLEY, VALLEY AND DAWSON COUNTIES, MONT.



B. GRAVEL PIT AT WOLF POINT, MONT.



C. LOGLIKE CONCRETION IN FORT UNION FORMATION.

flood plain, were probably formed by the large river that occupied the Big Muddy Valley and received its water and load of sand and gravel directly from the front of the glacier to the north, near the end of the glacial epoch.[1] Along Eagle, Beaver, and Whitetail creeks, tributaries of the Big Muddy, there are at many places beaver dams, above which are long strips of flood plain called beaver-dam land.

The alluvium along the forks of Poplar River consists largely of reworked Flaxville gravel, and because of this gravel the streams can be easily forded at nearly all places.

Rock Creek has a long, narrow canyon so precipitous that it was considered to be too rough to survey by the surveyors of the Land Office. The upper end of this canyon is near Barr post office, above which the valley is broad and filled with alluvium.

Frenchman Creek, by far the largest stream entering Milk River from the north, rises far to the northwest in Canada and after crossing the international boundary flows in a comparatively narrow valley which has probably been eroded since the last glacial advance. The flood plain along it is in general narrower than the flood plains of most of the other streams.

Whitewater Creek, farther west than Frenchman Creek, was probably situated in about its present course before the advance of the large Wisconsin glacier. Its valley is at least a mile wide and is filled by an extensive glacial moraine. Cottonwood Creek in its lower part has a comparatively narrow flood plain; the upper part of its course is called Woody Island Coulee. The water in this coulee apparently at one time flowed eastward and entered the valley of Whitewater Creek, but its old channel was blocked with glacial drift, and only one or two lakes are left to indicate its former position.

Beaver Creek, which enters Milk River from the south, occupies a broad valley bedded with silt, making the stream difficult to ford. The lower part of this valley coincides with that of the Musselshell, which before the advance of the Wisconsin glacier flowed into the Missouri in the valley of Milk River. The upper part of the valley of Beaver Creek from T. 27 N., R. 30 E., to the Coburn ranch, in T. 25 N., R. 26 E., is largely filled with glacial till, in which the creek is at places intrenched about 20 feet. In preglacial time it probably reached the old channel of the Missouri by way of Alkali Creek. For about 12 miles from T. 27 N., R. 30 E., to T. 26 N., R. 32 E., Beaver Creek occupies a narrow valley cut in the Bearpaw shale.

Larb Creek, east of Beaver Creek, occupies a very broad valley, and its bed is cut in alluvium. There is an easy pass from its head over the divide to the present course of the Missouri, as there is also from Beaver Creek.

SOIL OF THE UPLANDS.

The soil on the plateau surfaces of the region varies with the character of the underlying rock. The most interesting soil is that which caps the Flaxville gravel. This soil is from a few inches to several feet thick and has a slightly dark color. It is bound together by grass roots in its upper part and contains the bones of the bison. With the exception of that on the Boundary Plateau, this soil does not appear to contain much glacial material. South of Glasgow there is an extensive upland surface beneath which lies the Bearpaw shale, but here there is a sandy soil which owes its origin in part to the advance of the ice. Over much of the western part of the area there is a gumbo soil derived directly from the Bearpaw shale which it overlies. The soil on the Larb Hills is sandy, being derived from the disintegration of the Lance formation underlying it, mixed with a small amount of glacial material. The soil overlying the Judith River formation is sandy and not quite so good as that which overlies the Fort Union and Lance formations.

In the parts of the region covered by glacial moraines many small lakes have been filled since the retreat of the ice. The filling is generally grass and other plants that have grown in the water, together with materials that have blown from the sides. These old lake beds are in many places used for farm lands. In the large moraine-covered area, which has its center around Whitewater Creek a great many of these lakes are still unfilled, and water persists in them throughout the average summer.

STRUCTURE.

The Bowdoin dome,[2] northeast of Malta, in the western part of the region, is the most obvious structural feature, and from it the strata dip away in all directions. The dips are usually less than 1°, and where they have been determined by careful instrumental surveys they are best recorded in feet to the mile. The Little Rocky Mountains, about 40 miles southeast of the Bowdoin dome, present an abrupt uplift of the strata accompanied by an intrusion of igneous rocks, forming a laccolith, but this disturbance does not extend far from the base of the mountain. The beds around this uplift are tilted at angles in some places as high as 70°. The relation of the Bowdoin dome to the structure prevalent in the Little Rocky Mountains is shown in figure 6.

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[1] Rose, Bruce, Wood Mountain-Willowbunch coal area, Saskatchewan: Canada Geol. Survey Mem. 89, p. 50, 1916.

[2] Collier, A. J., The Bowdoin dome, Montana, a possible reservoir of oil or gas: U. S. Geol. Survey Bull. 661, pp. 193-209, 1917 (Bull. 661-E).

In the area immediately surrounding the Bowdoin dome the field work has not been in sufficient detail to ascertain whether or not there are minor structural features, but such features are known to exist in the eastern part of the region. The Poplar dome, on Missouri River, described by Smith,[1] is evidently such a feature, as it brings up a large elliptical area of Bearpaw shale nearly surrounded by the Lance formation. The formations immediately concerned dip away from it in all directions. The lignite beds along the river east of Brockton dip eastward at about 100 to 135 feet to the mile. In directions other than east of the dome, where its presence only intensifies the general dip, its effect does not reach farther than 15 miles away and probably the dips are much lower than those to the east. Similar small undulations of the strata can be inferred from the distribution of the Lance and Fort Union outcrops north of the Poplar dome, and several such features, which are not readily detected, were found in the course of mapping the lignite beds.

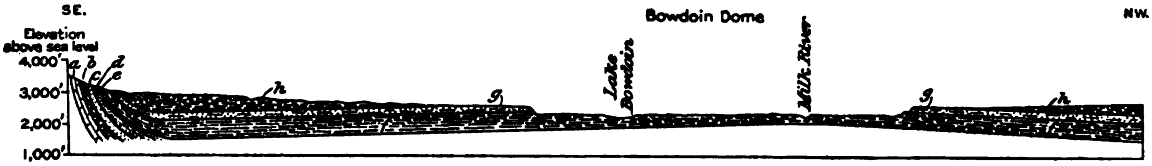

FIGURE 6.—Relations of the Bowdoin dome to the structure prevalent in the Little Rocky Mountains, Mont. *a*, Madison limestone; *b*, Ellis formation; *c*, Kootenai (?) formation; *d*, Colorado group; *e*, Eagle (?) sandstone; *f*, Claggett shale; *g*, Judith River formation; *h*, Bearpaw shale.

In the vicinity of Scobey, where the general dip of the rocks is toward the east, there is a westward dip for about a mile. Northeast of Scobey, south of Coal Creek, a small dome having a maximum width of about 2 miles is present. In the valley of Big Muddy Creek similar variations occur in the strike and dip. Such features probably are present in the western part of the region but they are very difficult to find because most of the rocks exposed are shale, in which it is practically impossible to trace individual beds for any distance.

Two small faults having a displacement of less than 15 feet each may be seen on the north side of Coal Creek in T. 37 N., R. 45 E., and a third fault of similar proportions displaces one of the lignite beds near the northwest corner of T. 36 N., R. 52 E. No other faults are known in either the eastern or the western part of the area of flat-lying beds, though they may be present. In the escarpments of the Flaxville plateau and the late Pliocene or early Pleistocene bench large blocks of strata may break away from their natural position and slump, giving the appearance of a condition which might result from faulting. This has occurred at many places in the Judith River formation around the Bowdoin dome. Faults of great displacement were seen in the Little Rocky Mountains and in the writer's opinion are common there, but they can not be described without further work in the field.

A word should be said in regard to the structure of the Larb Hills. Calhoun[2] makes the statement that these hills represent a dome whose character is similar to that of the Little Rocky Mountains but which is not eroded sufficiently to expose the underlying rocks. This statement is incorrect, for the Larb Hills are simply an outlier of the large area of Lance and Fort Union rocks exposed south of Missouri River, and the strata here have a uniformly low dip to the south. It is assumed, therefore, that Calhoun did not make a personal examination of these hills but relied on information obtained from some other source.

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[1] Smith, C. D., The Fort Peck Indian Reservation lignite field, Mont., U. S. Geol. Survey Bull. 381, p. 44, 1910.

[2] Calhoun, F. H. H., op. cit., p. 12.

The major part of the present structure in both the large flat-lying portions of the formations and the highly upturned portions in the Little Rocky Mountains was introduced subsequent to the deposition of the Fort Union formation and before that of the Oligocene gravel in the Cypress Hills, for this gravel rests unconformably upon the eroded surfaces of the Fort Union, Lance, and Bearpaw formations indiscriminately. In other words, this revolution occurred in late Eocene time. That a minor part of the folding may have been accomplished since the deposition of the Flaxville gravel is indicated by the fact that some of the streams in the eastern part of the region occupy synclinal valleys and by the absence of the Flaxville gravel between Opheim and the Boundary Plateau, it being assumed that an uplifted portion of the plateau would be more subject to erosion than the lower-lying part.

ADJUSTMENTS OF DRAINAGE.

Most stream adjustments in northeastern Montana are due to the invasion of ice during the glacial epoch. One of the most obvious features of this kind can be seen on Wolf Creek, a tributary of the Big Muddy, for its headwaters have been diverted and captured by the South Fork of Eagle Creek, largely because of glacial drift piled across its valley in secs. 8 and 9, T. 34 N., R. 51 E. Reference has been made to the change in the course of Woody Island Coulee, in T. 36 N., R. 28 E., by the filling up of its valley with glacial drift and to a possible old course of the headwaters of Beaver Creek by way of Alkali Creek to Milk River, a short distance above Malta.

The most pronounced stream adjustment in this region, however, is the diversion of Missouri River from the Milk River valley, which Calhoun[1] has described. The present valley of the Missouri south of the Larb Hills is practically a canyon 800 feet deep and not more than 2 miles across from rim to rim, whereas its old valley, now occupied by Milk River, is much broader and shallower. Before the river was diverted Musselshell River flowed into it by way of the lower portion of the Beaver Creek valley. By this change about 70 miles of the lower part of Musselshell River was diverted. Larb Creek was probably a much larger stream heading south of the Missouri and passing through the Larb Hills by way of the Timber Creek valley. The glacier from the north filled the whole of the Milk River valley and was thick and active enough to cover the Larb Hills with glacial drift. At its front the great volume of water due to melting ice and an attendant moist climate easily eroded a new channel in the soft Lance formation and Bearpaw shale. A view south across the gorge of the Missouri, 700 to 800 feet in depth, is shown in Plate VI, *A*.

An old channel of the Missouri from Culbertson to Lakeside, which is followed by the Great Northern Railway, and a broad depression extending from the Big Muddy Valley at Medicine Lake northwestward, crossing the State boundary about 6 miles south of the Canada line, have been described by Beekly.[2] The course of the depression is marked by a chain of shallow intermittent lakes. Bauer[3] has assumed that this feature also is an old channel of the Missouri, in which it flowed northward to Hudson Bay by way of Souris and Assinniboine rivers before the glacial epoch. The south end of this depression near Poplar has recently been inspected by Alden, who states[4] that its floor is about 200 feet above that of the present valley of the Missouri, and that its topography blends with the long slopes which characterize the early Pleistocene or late Pliocene bench of this region. Alden suggests that the river probably occupied this valley as long ago as the Pliocene epoch and that it was diverted at the time of the first invasion of ice early in the Pleistocene. The late Pliocene or early Pleistocene gravel described on pages 35–36 was probably laid down in or near the channel of one of the streams which contributed to form this river.

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[1] Calhoun, F. H. H., op. cit., pp. 34–45.

[2] Beekly, A. L., The Culbertson lignite field, Mont.: U. S. Geol. Survey Bull. 471, pp. 320–323, 1912.

[3] Bauer, C. M., A sketch of the late Tertiary history of the upper Missouri River: Jour. Geology, vol. 23, pp. 52–58, 1915.

[4] Alden, W. C., oral communication.

DEPOSITS OF CLAIBORNE AND JACKSON AGE IN GEORGIA.

By Charles Wythe Cooke and Harold Kurtz Shearer.

INTRODUCTION.

In 1911 the Geological Survey of Georgia published as Bulletin 26 a "Preliminary report on the geology of the Coastal Plain of Georgia," by Otto Veatch and Lloyd William Stephenson, prepared in cooperation with the United States Geological Survey under the supervision of T. Wayland Vaughan, geologist in charge of Coastal Plain investigations, who contributed the determinations of the invertebrate fossils of the Tertiary and Quaternary formations. Although this report constituted a decided advance in our knowledge of the geology of the Coastal Plain of Georgia, it was admittedly of reconnaissance character, and corrections and additions to it were to be expected. During the last few years field work has been prosecuted vigorously in the Coastal Plain of Georgia, and the additional information thus accumulated throws light upon certain problems of stratigraphy left unsolved by Veatch and Stephenson and alters considerably some of their correlations. The object of the present paper is to present the new evidence regarding the age and correlation of the Eocene formations of Georgia and to revise in accordance with present knowledge the descriptions of the deposits of Claiborne and Jackson age.

SUMMARY OF EOCENE AND LOWER OLIGOCENE FORMATIONS AS KNOWN TO 1911.

The chapters on the Eocene and lower Oligocene formations in the Coastal Plain report will be briefly summarized. Veatch and Stephenson recognized the following formations:

- Lower Oligocene:
  - Vicksburg formation.
- Eocene:
  - Jackson formation.
  - Claiborne group.
    - Barnwell sand.
    - McBean formation.
      - Congaree clay member (at base).
  - Wilcox formation.
  - Midway formation.

The Midway and Wilcox formations are confined to the region west of Perry, Houston County. East of Perry both formations are overlapped by younger strata.

The McBean formation of Veatch and Stephenson consists mainly of clays in the nature of fuller's earth, of marls, sandy limestones, and calcareous glauconitic sands. An extensive marine fauna containing many characteristic lower Claiborne mollusks occurs in the marls on McBean Creek, Burke County, and also in the lower part of Shell Bluff on Savannah River. A series of fuller's earth grading into calcareous clay which is exposed at short intervals from Grovetown, Columbia County, southwestward along the Fall Line to Bibb and Twiggs counties, was correlated on lithologic grounds with Sloan's Congaree "phase" of the South Carolina Eocene and designated the "Congaree clay member of the McBean formation."

The Barnwell sand, correlated with Sloan's Barnwell "phase" in South Carolina, consists largely of unconsolidated red and varicolored sands, with some indurated beds of gray sandstone and lumps of silicified limestone or flint. They stated that it overlies directly the McBean formation and is in contact with both the marls and the "Congaree" clay member of that formation, but the nature of the contact had not been satisfactorily determined. In places the Barnwell overlaps the McBean formation and rests directly upon the Lower Cretaceous. It carries a marine fauna which contains a number of species in common with the Gosport sand of Alabama (upper Claiborne) and was correlated with that formation.

The Jackson formation as originally mapped by Veatch and Stephenson included a small patch on Chattahoochee River, a small outlier on the Cretaceous at Rich Hill, Crawford County, and a long, narrow area running from a point about 8 miles southwest of Sandersville to a point 6 miles east of Montezuma. On the map accompanying the report on the ground waters of the Coastal Plain of Georgia by the same authors[1] this area was extended into southwestern Sumter County.

The Vicksburg formation of Veatch and Stephenson included besides strata of true Vicksburg age the great mass of limestone underlying the lower drainage basin of Flint and Chattahoochee rivers and forming the northern extension of the Ocala limestone of Florida.

RECENT INVESTIGATIONS AND THE INCEPTION OF THE PRESENT WORK.

The recent discovery that the Ocala limestone is of Jackson age[2] has largely increased the known areal extent of the deposits of that age, at the expense of the Vicksburg formation. The area of deposits of Jackson age has been further extended by Brantly,[3] to include most of those parts of Wilkinson and Twiggs counties formerly mapped as Claiborne. Brantly also expressed the opinion that the "Congaree" clay of previous reports seems to be the continuation of the Jackson limestone and fuller's earth of Houston County.[4] The same opinion concerning the stratigraphic relations of the "Congaree" clay was reached by H. K. Shearer, assistant State geologist, in the course of field investigations of the fuller's earth deposits of Georgia,[5] but as the published correlation of the "Congaree" clay with the Claiborne group seemed to be supported by as good paleontologic evidence as the correlation of the limestone with the Jackson, he was uncertain to which epoch the fuller's earth deposits properly belong.

At the request of Prof. S. W. McCallie, State geologist of Georgia, C. Wythe Cooke was assigned by the United States Geological Survey to accompany Mr. Shearer over the field, with the object of reconciling the discrepancies between the apparent stratigraphic relations of the deposits in eastern and central Georgia as determined by Messrs. Brantly and Shearer and the ages indicated by previously published lists of fossils.

Field work was done by the writers jointly from March 20 to April 19, 1916, and during that time all the most significant known exposures of Eocene strata in the region between Flint and Savannah rivers were visited and collections of fossils were made wherever possible.

The succeeding fortnight was spent by Mr. Cooke in visiting the type localities of the South Carolinian Eocene for the purpose of determining the propriety of applying the names Congaree and Barnwell to geologic formations in Georgia. Mr. Shearer subsequently examined the Claiborne deposits in Georgia west of Flint River. The results of Mr. Cooke's previous (1914) studies of the Ocala limestone are also incorporated in this paper.

The writers are indebted to Prof. E. W. Berry, of Johns Hopkins University, and to Dr. R. S. Bassler, of the National Museum, for reports on the plant remains and Bryozoa, respectively, and to Dr. Joseph A. Cushman for identifications of the Foraminifera. The other fossils collected in the course of this investigation have been identified by Mr. Cooke, who has also had the privilege of examining the collections in the National Museum upon which were based the correlations published in the preliminary report on the geology of the Coastal Plain of Georgia. The present paper was prepared under the direction of T. Wayland Vaughan, geologist in charge of Coastal Plain investigations of the United States Geological Survey, who has given it continuous personal attention and has made a number of suggestions that have been adopted by the writers.

CRITICAL SECTIONS AND EOCENE FAUNAS OF EASTERN GEORGIA.

DRY BRANCH.

In the vicinity of Dry Branch, Twiggs County, are good exposures of Eocene beds which were referred to the Claiborne group by Veatch and Stephenson, on the basis of Vaughan's identifications of the fossils, but which later discoveries have shown to be of Jackson age. The following section is typical. The formation names used are those adopted in this report.

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[1] U. S. Geol. Survey Water-Supply Paper 341, pl. 3, 1915.

[2] Cooke, C. W., The age of the Ocala limestone: U. S. Geol. Survey Prof. Paper 95, pp. 107-117, 1915.

[3] Brantly, J. E., Report on the limestones and marls of the Coastal Plain of Georgia: Georgia Geol. Survey Bull. 21, 1916.

[4] Idem, p. 8.

[5] Since the completion of this manuscript Shearer's report on the bauxite and fuller's earth of the Coastal Plain of Georgia has been published as Bulletin 31 of the Georgia Geological Survey. He has adopted the correlations proposed here.

Section at the mines of the Georgia Kaolin Co., 2 miles east of Dry Branch.

	Feet.
Vicksburg or Barnwell formation:	
7. Red sand, capping hill, about	80
Barnwell formation (Twiggs clay member):	
6. Greenish-gray fuller's earth (buff when dry)	30-40±
Ocala limestone (Tivola tongue):	
5. Impure white argillaceous limestone, grading into fuller's earth. Pinches out toward the north and northwest and is absent in the northwestern part of the quarry. Contains many Bryozoa. Separated from the underlying bed by a somewhat irregular contact	0- 5
Barnwell formation (lower part):	
4. Yellow sand with black carbonaceous stains. Contains a few large bones of *Basilosaurus cetoides* (Owen)[1]	1- 2½
3. Yellow to red sand, medium coarse, irregularly bedded	12
2. Gray sandstone with calcareous cement, loaded with casts of mollusks. Pinches out at north end of quarry, where the kaolin is overlain by glauconitic sand	0- 2
Unconformity.	
Lower Cretaceous:	
1. White kaolin	15-20

The fossils collected from the basal Eocene at this locality are listed below.

Station 7691. Pit of Georgia Kaolin Co., 2 miles east of Dry Branch, Ga. Bed 2 of section. Basal sandstone immediately overlying the Lower Cretaceous. Cooke and Shearer, collectors, 1916.

Levifusus trabeatus (Conrad)?
Levifusus sp.
Ficus filius (Meyer).
Turritella sp.
Mesalia vetusta (Conrad).
Calyptraea sp.
Nucula magnifica Conrad.
Leda cf. L. mater Meyer.
Leda cf. L. plicata (Lea).
Leda regina-jacksonis Harris?
Glycymeris staminea (Conrad)?
Glycymeris sp.
Barbatia cuculloides (Conrad).
Ostrea trigonalis Conrad.
Ostrea sp.
Pteria limula (Conrad)?
Panope porrectoides (Aldrich).
Corbula oniscus Conrad var.
Corbula densata Conrad.
Phacoides (Miltha) pandatus (Conrad).
Phacoides alveatus (Conrad) var.
Phacoides (Here) sp.
Tellina, 2 sp.
Macoma sp.
Metis sp.
Tagelus sp.
Meretrix securiformis (Conrad)?
Protocardia nicolleti (Conrad).

Many of the mollusks in this list occur in both Claiborne and Jackson deposits, but *Ficus filius*, *Leda mater*, *Leda regina-jacksonis*, *Ostrea trigonalis*, *Meretrix securiformis*, and *Protocardia nicolleti* are particularly characteristic of the Jackson and are rare or unknown in older beds. *Mesalia vetusta*, which had been previously thought to be confined to the upper Claiborne (Gosport greensand horizon), has recently been found at the base of the Jackson formation at Sims, Yazoo County, Miss.

Basilosaurus cetoides, the zeuglodon, which occurs in bed 4, is so far as known confined to the Jackson, and in most places is most abundant near the top.

According to R. S. Bassler, the Bryozoa in bed 5 constitute a fauna peculiar to the middle Jackson. The same fauna occurs at Rich Hill, Crawford County, and numerous other localities in central Georgia and will be referred to for convenience as the Rich Hill facies of the Jackson fauna.

The fuller's earth of bed 6, a greenish hackly clay of low specific gravity, resembles the beds exposed at numerous localities in central and eastern Georgia and referred by Veatch and Stephenson to the "Congaree" clay member of the McBean formation.

The red sand at the top of the section was correlated by Veatch and Stephenson with the Barnwell sand, and the underlying beds were placed doubtfully with the McBean formation.[2]

Certain problems in stratigraphy, which the authors cited were unable to explain under the supposition that the strata near Dry Branch are of Claiborne age, vanish immediately when it is discovered that the deposits are of Jackson age. For instance, they say:[3]

> According to Dr. Vaughan the evidence of the fossils shows that Jackson strata occur near the mines of the Georgia Kaolin Co., 2 miles southeast of Dry Branch. There is an exposure of 15 feet of soft white argillaceous marl in a small ravine one-half mile southeast of the clay-working plant, which contains Bryozoa and other fossils and is similar lithologically to the marl at Rich Hill. It lies 10 to 15 feet above the white clay beds of the Cretaceous and is overlain by 125 feet of bluish or drab laminated sandy clay and red sand, the clay containing thin slabs of quartzite or sandstone. In this vicinity Claiborne fossiliferous strata occur at both higher and lower levels than this marl, and the presence of Jackson beds in this

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[1] Identified by C. W. Gilmore.

[2] Veatch, Otto, and Stephenson, L. W., Geology of the Coastal Plain of Georgia: Georgia Geol. Survey Bull. 26, p. 256, 1911.

[3] Idem, p. 304.

position implies either a deep erosion unconformity between the two formations or a flexure. Exposures in this vicinity, so far as they have been examined, afforded no evidence of an unconformity or of any faulting or folding of the beds. Further detailed field work is necessary to solve this problem of stratigraphy.

The problem has been solved by the discovery that the beds higher and lower than the marl are Jackson and not Claiborne.

SOUTH OF PERRY.

Other localities which presented difficulties to Veatch and Stephenson are Mossy Hill and Ross Hill, in Houston County. These hills are a few miles apart on the escarpment south of Mill and Flat creeks, which extends northeastward, approximately parallel to the general strike of the formations of the Coastal Plain in this part of the State. Ross Hill is crossed on the road from Perry to Elko, 3 miles south of Perry, and Mossy Hill lies on the National Highway (the road from Perry to Henderson) about 5.7 miles southwest of Perry.

The entire section at Ross Hill, with the exception of 10 feet at the top, was referred by Veatch and Stephenson to the Jackson formation, and this correlation was supported by lists of fossils identified by Vaughan. The following section measured by the writers is in essential agreement with that of Veatch and Stephenson.[1] The base of the section is 25 feet above Mill Creek.

Section on Perry-Elko road at Ross Hill.

	Feet.
Oligocene (?):	
Vicksburg formation (?):	
7. Concealed to edge of plowed field on top of hill, which rises a few feet higher. The surface is strewn with lumps of sparingly fossiliferous chert	15
Eocene (all of Jackson age):	
Barnwell formation:	
6. Soft cream-colored to yellow sandy limestone with casts of fossils. *Lunularia distans*, *Endopachys*, *Calyptraea*, *Leda*, and *Pecten*	4±
5. Light-colored limestone at base; upper part concealed but with débris of soft limestone with *Periarchus pileus-sinensis* and Bryozoa	15
4. Hackly cream-colored calcareous clay (fuller's earth) with lime concretions	24
Ocala limestone (Tivola tongue):	
3. Cream-colored limestone, soft when fresh, with a hard ledge at bottom. Has been quarried in part. Contains *Pecten perplanus* and many Bryozoa	7½
2. Soft greenish-yellow limestone, speckled with glauconite and with locally indurated nodules or ledges. Very argillaceous toward the top and contains numerous soft, irregular lime concretions. Bryozoa	7½
1. Pale cream-colored soft limestone, replete with Bryozoa (Rich Hill facies of Jackson fauna). Hard ledges near the top. Contains also *Periarchus pileus-sinensis*. Exposed east of the road	38

The following section was measured in a gully on Ross Hill about 300 yards west of the Perry-Elko road. The top of the hill here is probably 40 feet or more higher than at the road. The base of the section is by barometer 40 feet above the bridge over Mill Creek.

Section on Ross Hill 300 yards west of Perry-Elko road.

	Feet.
Oligocene (?):	
Vicksburg formation (?):	
14. Red sand with "buckshot" ferruginous lumps. Fragments of fossiliferous chert on top	30
Eocene:	
Barnwell formation (Twiggs clay member):	
13. Glauconitic clay and fuller's earth, poorly exposed	15±
12. Glauconitic grains in a matrix of yellowish, calcareous clay. *Pecten* sp., etc	2½±
11. Gray hackly clay (fuller's earth); upper 2 feet containing lenses or nodules of glauconitic material resembling bed 12	7½±
10. Lens or nodule of greenish-gray limestone with casts of *Corbula*, probably *C. wailesiana*	1
9. Fuller's earth	4
8. Limestone	1
7. Calcareous fuller's earth	15
6. Continuous ledge of gray limestone with poorly preserved mollusks	½
5. Calcareous fuller's earth containing soft, white chalk nodules	3½
4. Hard light-gray limestone, softer at bottom. Contains some Bryozoa, *Flabellum*, *Turritella carinata*, *Mesalia vetusta*, *Pecten*, *Meretrix*, and *Periarchus pileus-sinensis*	3
3. Hackly cream-colored calcareous clay (fuller's earth). The base of this bed is the same as the base of bed 4 of preceding section	35
Ocala limestone (Tivola tongue):	
2. Soft argillaceous limestone loaded with Bryozoa (Rich Hill facies of Jackson fauna). Contains also *Ostrea trigonalis* and *Pecten perplanus*	7
1. Hard and soft ledges of limestone with Bryozoa, *Pecten perplanus*, and *Periarchus pileus-sinensis* very abundant	17

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[1] Op. cit., p. 301.

Bed 4 is particularly significant in that it shows the presence of *Turritella carinata* and *Mesalia vetusta,* which were considered by Vaughan to be diagnostic upper Claiborne fossils, well above the base of the deposits of Jackson age.

The geologic conditions at Mossy Hill appear to be similar to those at Ross Hill, but the exposures are less complete. The following section, exposed in and near an old quarry about 100 yards east of the National Highway, extends from a gully below the quarry to a level bench on the road.

Section at Mossy Hill.

Oligocene, Vicksburg formation:	
13. Red argillaceous sand with chert fragments, commencing at a level bench on the National Highway and capping the upland area to the south	30
Eocene: Barnwell formation (Twiggs clay member):	
12. Mostly concealed, but interbedded fuller's earth and bryozoan limestone are exposed in a gully east of the road a few feet below the bench	25
11. Yellow to green, partly indurated glauconitic marl	5
10. Calcareous clay resembling fuller's earth, with a locally indurated stratum at top	5½
9. Impure yellowish limestone with casts of fossils	2½
8. Concealed	6
7. Clay or fuller's earth with chalk concretions	2
6. Concealed	14
5. Calcareous fuller's earth, exposed on roadside	3
4. Hard limestone	½
3. Calcareous fuller's earth	2½
2 Argillaceous fossiliferous limestone with hard ledges; quarried	11
1. Gray calcareous clay with lime nodules below, grading upward into fuller's earth with lime nodules; exposed in gully below quarry	21

From bed 2 the following species were obtained:

Station 7682. Quarry on Mossy Hill. Cooke and Shearer, ollectors, 1916:

Endopachys sp.
Lunularia distans (Lonsdale).
Turritella carinata Lea.
Mesalia vetusta (Conrad).
Leda cf. L. plicata (Lea).
Glycymeris sp.
Pecten perplanus Morton.
Phacoides alveatus (Conrad).
Miltha claibornensis (Conrad).
Dentalium sp.

The stratum immediately below the bed from which these species were collected contains Bryozoa which R. S. Bassler refers to the horizon of the deposits of Jackson age at Baldock, S. C. The stratum in the quarry from which the fossils were collected seems to be identical with bed 4 of the section on Ross Hill west of the Perry-Elko road. Not only are the species, so far as they can be identified, the same, but the rocks in which they are embedded look alike, and the sections both above and below the fossiliferous zone are similar. Moreover, the topographic relations of the two localities are such as to indicate that the beds at both are at the same horizon, provided, of course, that there are no structural disturbances, of which there is no evidence.

In the Coastal Plain report[1] the lower part of the section at Mossy Hill was referred to the Claiborne group on the basis of collections of fossils made by T. W. Vaughan and S. W. McCallie. The species collected by Vaughan at Mossy Hill are listed as follows:

Flabellum cuneiforme Lonsdale.
Turbinolia pharetra Lea.
Endopachys maclurii (Lea).
*Turritella carinata Lea.
*Mesalia vetusta (Conrad).
Calyptraea aperta (Solander).
Dentalium thalloides Conrad.
Nucula ovula Lea.
Leda sp.
Leda sp.
Glycymeris idoneus (Conrad)?
*Phacoides alveatus (Conrad).
Venericardia, 2 or 3 sp.
Cytherea sp.
Crassatellites sp.
Corbula oniscus Conrad or wailesiana Harris.
Corbula densata Conrad?

Geologic horizon, Claiborne. Species marked * are not known from the Jackson.

It will be noted that the only species checked as not known from the Jackson are *Turritella carinata*, *Mesalia vetusta*, and *Phacoides alveatus*. The first and second have since been found in the beds of Jackson age at Ross Hill, and the second and third at the mine of the Georgia Kaolin Co. One of the undetermined species of *Leda* listed occurs also at the latter place.

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[1] Veatch, Otto, and Stephenson, L. W., op. cit., pp. 258-260.

The fossils collected by McCallie are listed as follows:

Turbinolia pharetra Lea.
Flabellum cuneiforme Lonsdale.
Plejona petrosa (Conrad).
*Turritella carinata Lea.
Mesalia vetusta (Conrad).
Dentalium thalloides Conrad.
Nucula ovula Lea.
Leda.
*Glycymeris trigonella (Conrad).
Pteria sp.
*Phacoides alveatus (Conrad).
*Phacoides aff. P. clairbornensis (Conrad).
Venericardia planicosta Lamarck.
*Venericardia alticostata (Conrad).
Cytherea sp.
*Crassatellites protextus (Conrad).
*Corbula oniscus Conrad.
*Pteropsis lapidosa (Conrad).

Species marked * are not known from beds above the Claiborne. *Pteropsis lapidosa* is characteristic of the lower Claiborne.

This does indeed look like a Claiborne fauna, and with the data then available Vaughan was perfectly justified in referring these fossils to the Claiborne group; but, as we shall see later, nearly all the species checked have since been found associated with Jackson fossils. The exception to these is *Pteropsis lapidosa,* which elsewhere seems to be confined to the lower Claiborne. As this collection of fossils apparently is not now in the National Museum, the identifications of the species could not be checked nor could the matrix be examined to ascertain whether there had been accidental mixture of specimens from different localities.

There is some uncertainty as to the locality at which the fossils ascribed to Mossy Hill were obtained. According to Veatch and Stephenson,[1] Mossy Hill is on the Perry-Elko road 4½ miles south of Perry, a location corresponding nearly with that of Ross Hill. However, as there seems to be little doubt that the horizon is the same as that from which the writers obtained *Turritella carinata* and *Mesalia vetusta,* the exact locality is of no particular importance.

VICINITY OF GIBSON.

A collection made by the writers from sandstone ledges exposed on the hillside east of Rocky Comfort Creek, on the Brassell property, 2 miles northeast of Gibson, Glascock County, shows the presence in Georgia of a fauna not previously recognized east of Arkansas. The fossils are preserved in the form of hollow molds or siliceous pseudomorphs, some of which have weathered out of the sandy matrix. The rock, which is an indurated facies of the basal sand bed of the Eocene that is of widespread distribution in this part of the State, is exposed to a thickness of 3 or 4 feet but probably extends somewhat deeper. It lies not far above the Cretaceous, but the contact is not exposed here. The fossils collected are enumerated in the accompanying list, in which the initials C and J signify that the species so marked occur elsewhere in Claiborne and Jackson deposits, respectively.

Station 7710. Brassell property, 2 miles northeast of Gibson, Glascock County. Cooke and Shearer collectors, 1916.

CJ Flabellum cuneiforme Lonsdale.
J Astrhelia burnsi Vaughan?
CJ Cancellaria gemmata Conrad.
Olivella sp.
CJ Marginella semen Lea?
Psilocochlis mccalliei (Dall).
CJ Lapparia pactilis (Conrad).
CJ Plejona petrosa (Conrad).
J Levifusus branneri Harris.
CJ Levifusus trabeatus (Conrad).
CJ Mazzalina inaurata (Conrad) var.
Fusinus aff. F. bellus (Conrad).
J Murex marksi Harris.
CJ Pseudoliva vetusta (Conrad).
CJ Calyptraphorus velatus (Conrad).
Cerithium sp.
J Ficus filius (Meyer).
CJ Turritella carinata Lea.
CJ Mesalia vetusta (Conrad).
CJ Natica minima Lea.
J Natica permunda Conrad?
Dentalium sp.
J Leda regina-jacksonis Harris.
CJ Leda multilineata Conrad?
CJ Glycymeris staminea (Conrad)
CJ Pteria limula (Conrad).
Crenella sp.
Pecten n. sp.
CJ Corbula densata Conrad.
CJ Phacoides (Miltha) claibornensis (Conrad).
Phacoides sp.
CJ Crassatellites protextus (Conrad) var.
Crassatellites n. sp?
CJ Macrocallista perovata (Conrad)?
CJ Venericardia planicosta (Lamarck).
C Venericardia alticostata Conrad var.

To this list should be added the following, which were obtained with other fossils from the same horizon at station 7711, on the east side of Deep Creek, 3½ miles northeast of Gibson and about 1½ miles from the Brassell locality:

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[1] Op. cit., p. 258.

J Turritella clevelandia Harris.
Leda plicata (Lea) var.
Trinacria? sp.
J Corbula wailesiana Dall.

The section there is as follows:

Section on roadside east of Deep Creek, 3½ miles northeast of Gibson.

	Feet.
Eocene (Barnwell formation):	
7. Mottled red or orange-colored sand	50±
6. Fuller's earth with sand laminae	11
5. Unconsolidated sand similar to No. 4	5
4. White or gray fossiliferous sandstone like that on Brassell property	6
3. Gray clayey sand	4
2. Concealed	10
Cretaceous:	
1. Kaolin and white sand	15

This fauna, which occurs within 15 feet of the Eocene-Cretaceous unconformity, bears a remarkably close resemblance to that occurring at White Bluff and Crowleys Ridge, Ark., which was formerly referred to the Claiborne group but is now correlated with the lower Jackson.[1] It is rather surprising to encounter such species as *Levifusus branneri*, *Murex marksi*, and *Turritella clevelandia*, which are typical of the Jackson deposits in Arkansas, so far east of their previously known range; but their presence, as well as the general aspect of the fauna, is good evidence that the beds containing them occupy approximately the same stratigraphic position. The presence of *Astrhelia burnsi*, *Ficus filius*, *Natica permunda*, *Leda regina-jacksonis*, and *Corbula wailesiana* affords strong additional evidence that the deposits are of Jackson age.

It will be noted that this list, which is much more comprehensive than any previously compiled from this region, contains nearly all the species that were considered by Vaughan to be diagnostic of the upper Claiborne. There are, in addition, a few species that are abundant at this horizon in Georgia but have not yet been found elsewhere. Among these may be mentioned *Psilocochlis mccalliei* and an undescribed species of *Pecten* which has hitherto been confused with *Pecten wilcoxii* and *P. wahtubbeanus*.

Fossils representing this same horizon and embedded in a similar matrix of gray sandstone which were collected by McCallie on the English plantation, 1½ miles north of Gibson, were referred by Veatch and Stephenson[2] to the McBean formation. The revised list follows:

Station 3943. English plantation, 1½ miles north of Gibson. S. W. McCallie, collector, 1904.
Flabellum cuneiforme Lonsdale.
Endopachys maclurii (Lea).
Mazzalina inaurata (Conrad).
Plejona petrosa (Conrad).
Turritella clevelandia Harris.
Turritella sp.
Pecten n. sp.
Pteria limula (Conrad)?
Panope sp.
Phacoides (Miltha) clabornensis (Conrad).
Venericardia alticostata Conrad var.

The same fauna has been recognized at several localities between Glascock and Bibb counties and is usually found in more or less indurated gray sandstone resembling that near Gibson. All these exposures were referred by Veatch and Stephenson to the Claiborne group—some to the McBean formation, others to the Barnwell sand.

BROWNS MOUNTAIN AND VICINITY.

At Browns Mountain, Bibb County, 9 miles southeast of Macon, the strata were referred to the Barnwell sand.[3]

At this locality the main exposures consist of about 20 feet of hard gray sandstone, part of which appears to grade into sandy limestone. It contains fossils that are locally abundant but are not very well preserved. Above the sandstone are poor exposures of bryozoan limestone with *Pecten perplanus?*. Beneath the sandstone are incomplete exposures of fuller's earth and sand.

The relations are more evident on a hill on the Marion road, four-tenths of a mile southwest of Bond's store, where the following section was observed:

Section on Marion road 9 miles southeast of Macon.

	Feet.
Eocene:	
6. Hard sandstone and quartzite, to top of hill	7
5. Mottled plastic clay	3
4. Red sand	4
3. Soft fossiliferous sandstone	0–4
2. Basal conglomerate; white kaolin pebbles in cross-bedded sand. Contact with Cretaceous not precisely located because of lithologic similarity	55
Cretaceous:	
1. Coarse white kaolinic sand to stream level	65

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[1] Stephenson, L. W., and Crider, A. F., Geology and ground waters of northeastern Arkansas: U. S. Geol. Survey Water-Supply Paper 399, pp. 73–84, 1916.

[2] Op. cit., p. 273.

[3] Idem, pp. 258–260.

Stratum 3 of the section consists of a discontinuous ledge of sandstone which in places is reduced to lumps embedded in incoherent sand. It contains casts of mollusks, including *Pecten* n. sp. Bed 6 is also unequally indurated but is more persistent than bed 3. It carries *Periarchus pileus-sinensis* and other fossils. Beds 3 to 6 are equivalent to the hard rock on Browns Mountain, half a mile away.

The following lists enumerate the species collected in this vicinity:

Station 7695. Hilltop on Macon-Marion road four-tenths of a mile southwest of Bond's store, Bibb County. C. Wythe Cooke, collector, 1916.
- Nucula ovula Lea?
- Leda regina-jacksonis Harris?
- Glycymeris sp.
- Pecten n. sp.
- Cytherea sp.
- Periarchus pileus-sinensis (Ravenel)?

Station 7696. Browns Mountain, near Bond's store, 9 miles southeast of Macon. C. Wythe Cooke, collector, 1916.
- Flabellum cuneiforme Lonsdale.
- Lunularia sp.
- Turritella sp.
- Mesalia vetusta (Conrad).
- Calyptraea sp.
- Nucula spheniopsis Conrad.
- Leda mater Meyer.
- Pecten n. sp.
- Pecten perplanus Morton? (cast of interior).
- Diplodonta sp.
- Phacoides (Miltha) claibornensis (Conrad).
- Protocardia sp.
- Crassatellites sp.

Station 3993. Browns Mountain. S. W. McCallie, collector, 1909.[1]
- Flabellum cuneiforme Lonsdale.
- Endopachys maclurii (Lea).
- Periarchus pileus-sinensis (Ravenel).
- Calyptraphorus velatus Conrad.
- Turritella carinata Lea.
- Mesalia vetusta (Conrad).
- Calyptraea aperta (Solander).
- Nucula magnifica Conrad?
- Pteria sp.
- Pecten n. sp.
- Crassatellites protextus (Conrad) var.
- Astarte tellinoides Conrad?
- Venericardia alticostata Conrad var.
- Phacoides (Here) hamatus Dall.
- Phacoides alveatus (Conrad).
- Protocardia nicolleti (Conrad).
- Pitaria perovata (Conrad).
- Cytherea sp.
- Psammobia sp.
- Panope porrectoides (Aldrich).
- Corbula oniscus Conrad.

LITTLE KEG CREEK.

A large collection of fossils that is especially interesting because it shows the intimate relationships of the Claiborne and Jackson faunas was obtained on the east side of Little Keg Creek, 7 miles north-northwest of Sandersville. Without the knowledge of the extended range of certain species acquired since the publication of the report on the Coastal Plain of Georgia, this assemblage of forms would have been unhesitatingly referred to the upper Claiborne. As it stands, the numerical proportions of Claiborne and Jackson species recognized are practically the same, and the discovery of one or two additional species might turn the scale to one side or the other. When the numerical evidence is inconclusive in determining the age of a fauna, the philosophic course appears to be to attribute greater significance to the initial appearance of new forms than to the survival of old species. According to this reasoning the fauna at Keg Creek is lower Jacksonian, and it is so considered in this report. Moreover, this correlation is in accordance with that deduced from other stratigraphic criteria.

Section on east side of Little Keg Creek, Washington County, 7 miles north-northwest of Sandersville.

	Feet.
Eocene:	
4. Coarse red sand with a few small quartz pebbles; 40 feet above the base is a 10-foot bed of white sand and yellow and white clay..	100
3. Greenish plastic clay........................	6½
2. Coarse red sand grading into overlying bed. Fossils very abundant but restricted to 6 inches at bottom........................	1½
Unconformity (altitude 360 feet above sea level).	
Cretaceous:	
1. White sand with lenses of kaolin, to level of creek..................................	60

The fossils in the following list were collected from the base of bed 2, which is a local pocket filling a hollow in the Cretaceous surface.

Station 7707. Roadside east of Little Keg Creek, 7 miles north-northwest of Sandersville. Immediately above the Cretaceous. Cooke and Shearer, collectors, 1916:
- CJ Flabellum cuneiforme Lonsdale.
- J Astrhelia burnsi Vaughan.
- Astrhelia sp.
- Volvula sp.
- CJ Actaeon idoneus Conrad.
- Actaeon sp.
- Terebra sp.
- C Cochlespirella nana (Lea)?
- Turritidae, 3 sp.

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[1] Veatch, Otto, and Stephenson, L. W., op. cit., p. 295. Identified by T. W. Vaughan; list revised by C. W. Cooke.

Station 7707—Continued.
CJ Conus sauridens Conrad.
CJ Cancellaria gemmata Conrad.
Cancellaria, 2 sp.
Olivella sp.
C Ancillina scamba (Conrad).
CJ Marginella semen Lea.
Conomitra sp.
J Psilocochlis mccalliei (Dall).
Caricella n. sp.
CJ Plejona petrosa (Conrad).
CJ Lapparia pactilis (Conrad).
Fusinus sp.
Clavilithes sp.
CJ Levifusus trabeatus (Conrad)?
C Phos sagenus (Conrad).
C Terebrifusus amoenus (Conrad).
J Ficus filius (Meyer).
CJ Calyptraphorus velatus (Conrad).
Cerithiopsis sp.
CJ Turritella carinata Lea.
CJ Mesalia vetusta (Conrad).
Epitonium sp.
Turbonilla sp.
J Sinistrella americana (Aldrich)?
Calyptraea sp.
CJ Lunatia minima (Lea).
Neverita sp.
CJ Dentalium sp.
CJ Nucula magnifica Conrad?
CJ Nucula ovula Lea.
CJ Leda multilineata Conrad.
CJ Glycymeris staminea (Conrad).
Glycymeris sp.
C Crenella isocardioides (Lea).
CJ Corbula oniscus Conrad.
CJ Corbula densata Conrad.
C Corbula alabamiensis Lea.
C Corbula fossata var. extenuata Dall.
CJ Pitaria perovata (Conrad).
CJ Pitaria mortoni (Conrad).
CJ Miltha pandata (Conrad)?
CJ Lucina subvexa Conrad?
CJ Phacoides alveatus (Conrad)?
Astarte cf. A. tellinoides (Conrad).
CJ Crassatellites protextus (Conrad) var.
J Crassatellites n. sp.?
J Protocardia nicolleti (Conrad).
CJ Venericardia planicosta (Lamarck).
J Venericardia sp. (small).
CJ Venericardia alticostata Conrad var.

Sufficient evidence has been advanced in the preceding pages to show, first, that certain strata referred by Veatch and Stephenson to the McBean formation overlie limestones that are definitely of Jackson age and, second, that the fauna of the Barnwell formation appears to be more closely related to Jackson than to Claiborne faunas and that the fossiliferous beds at some places lie directly upon Lower Cretaceous strata.

Below is given a systematic outline of the stratigraphy of the deposits of Claiborne and Jackson age as it is interpreted in the light of the new evidence.

STRATIGRAPHY OF DEPOSITS OF CLAIBORNE AND JACKSON AGE IN GEORGIA.

DEPOSITS OF CLAIBORNE AGE.

FORMATIONS INCLUDED.

The Claiborne group receives its name from Claiborne Landing, Alabama River, Ala., the site of a town formerly of considerable importance but now almost deserted. In the type region the group is divided into three formations, the lowest being the Tallahatta buhrstone, the middle the Lisbon formation, and the upper the Gosport sand. The correlations between Alabama and Georgia are not precise enough to justify the use of any of these formation names in Georgia.

According to the interpretation of Veatch and Stephenson, nearly all the deposits of Eocene age in Georgia were included in the Claiborne group, and their map shows Claiborne formations extending across the entire width of the State. They recognized two formations within the group—a lower, the McBean formation with the so-called Congaree clay member, and an upper, the Barnwell sand. The recent detailed field studies of Shearer and Brantly have shown that the so-called "Congaree clay member of the McBean formation" properly constitutes part of the Barnwell formation, and studies of the fossils by Cooke, as set forth in the preceding part of this paper, have shown that the residue of their McBean formation in central Georgia also belongs to the Barnwell. The paleontologic evidence also indicates that the Barnwell formation is of Jackson rather than of upper Claiborne age, as previously supposed, and this conclusion is corroborated by diastrophic and other stratigraphic criteria.

As restricted by the elimination of the Barnwell formation and parts of the McBean formation the outcropping strata of Claiborne age in Georgia are confined to two separate areas—a small irregular area in the valleys of McBean Creek and Savannah River, in the extreme eastern part of the State, and a long, narrow strip in western Georgia, extending from Chattahoochee River eastward to a point a few miles beyond Flint River. In the intermediate region the Claiborne deposits are overlapped by strata of Jackson age. The beds of Claiborne age in the Savannah area retain the name McBean formation, but those in the Chattahoochee-Flint River area, which were included by Veatch and Stephenson in the McBean formation and Barnwell sand, will be designated in this report undifferentiated Claiborne. The areal distribution is shown on the geologic map (Pl. VII).

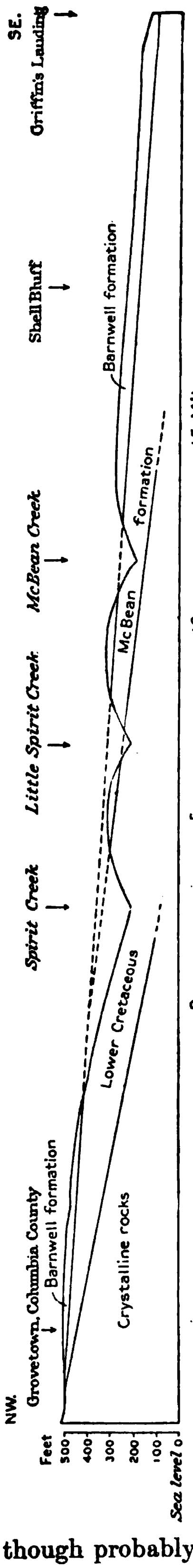

FIGURE 7.—Section from Grovetown to Griffin's Landing, Savannah River, Ga.

McBEAN FORMATION.

NAME.

The McBean formation was named by Veatch and Stephenson[1] from the town of McBean, in Richmond County, Ga., and from McBean Creek, which forms the boundary between Richmond and Burke counties.

STRATIGRAPHIC RELATIONS.

The McBean formation rests unconformably upon the Lower Cretaceous strata and is overlain by the Barnwell formation. The contact with the Barnwell is obscure, but it appears probable that there exists at least local unconformity between the two formations.

In the Savannah area the Claiborne strata have been overlapped by the Barnwell formation, though probably not so much as farther west, but the valley of Savannah River has been incised so deeply that the overlapping portion of the Barnwell formation has been cut away along the river far enough to expose the McBean in its proper position above the Cretaceous. (See section, fig. 7.)

LITHOLOGIC CHARACTER AND THICKNESS.

The McBean formation consists chiefly of gray marl or sandy limestone and yellow sand with a little lignitic matter and greenish clay. The greatest thickness thus far observed at one locality is not more than 80 feet, and the total stratigraphic thickness along the outcrop in Georgia probably does not greatly exceed 100 feet.

PALEONTOLOGIC CHARACTER.

A large collection of well-preserved shells, chiefly mollusks, was obtained by Earle Sloan on the south side of McBean Creek near the Augusta-Waynesboro road. On the basis of these shells Vaughan[2] correlates the strata with the Lisbon formation of Alabama and Mississippi, the St. Maurice formation of Louisiana, and the Cook Mountain formation of Texas. The same fauna has been found at several localities in Aiken and Orangeburg counties, S. C. The following list of species from Sloan's Scarp, McBean Creek, is quoted from the report on the Coastal Plain:[3]

Endopachys maclurii (Lea).
Ringicula biplicata (Lea).
Conus sauridens Conrad.
Pleurotoma kelloggi Gabb.
Pleurotoma texacona Harris.
Pleurotoma terebriformis Meyer.
Pleurotoma childreni Lea.
Pleurotoma lesueuri Lea.
Pleurotoma nodocarinata Gabb.
Pleurotoma aff. P. rugosa Lea.
Amblyacrum stantoni Vaughan.
Amblyacrum huppertzi var. penrosei Harris?
Mangelia infans Meyer.
Marginella columba Lea.
Marginella semen Lea.
Caricella demissa var. texana Gabb.
Caricella aff. C. pyruloides (Conrad).
Clavelithes humerosus Conrad.
Fusus bellus Conrad.
Fusus mortoni Lea.
Lirofusus thoracicus (Conrad).
Typhis gracilis Conrad.
Pyrula (Fusoficula) texana Harris.
Leiorhynus prorutus Conrad.
Laevibuccinum prorsum Conrad.
Mitrella mississippiensis Meyer and Aldrich.

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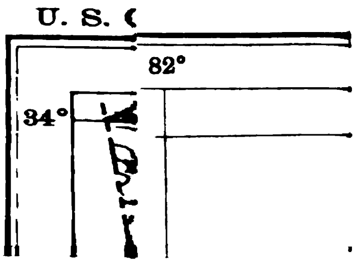
[1] Op. cit., p. 237.

[2] Idem, p. 240.

[3] Idem, pp. 239-240.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Phos sagenum (Conrad).
Buccinanops altile (Conrad).
Pseudoliva vetusta (Conrad)
Lacinia alveata Conrad.
Turritella nasuta Gabb.
Turritella nasuta var. houstonia Harris.
Turritella arenicola Conrad.
Turritella carinata Lea.
Mesalia claibornensis (Conrad).
Tuba antiquata Conrad.
Amalthea pygmaea (Lea).
Calyptrea aperta (Solander).
Crepidula lirata Conrad.
Lunatia eminula (Conrad).
Natica semilunata Lea.
Sigaretus declivis Conrad.
Solarium elaboratum Conrad (young).
Solariorbis depressa (Lea) var.
Dentalium annulatum Meyer.
Nucula ovula Lea.
Nucula magnifica Conrad.
Leda media Lea.
Yoldia psammotaea Dall.
Arca rhomboidella Lea.
Ostrea sellaeformis Conrad.
Pecten wahtubbeanus Dall.
Crassatellites protextus (Conrad).
Venericardia sp. (also at Lisbon, Ala.).
Venericardia alticostata (Conrad).
Venericardia planicosta Lamarck.
Phacoides papyraceus (Lea).
Bornia prima (Aldrich).
Cytherea discoidalis Conrad.
Metis raveneli (Conrad).
Tellina mooreana Gabb.
Pteropsis lapidosa Conrad.
Corbula alabamiensis Lea.
Corbula densata Conrad.
Corbula fossata var. extenuata Dall.

AREAL DISTRIBUTION, PHYSIOGRAPHIC EXPRESSION AND STRUCTURE.

So far as known, exposures of the McBean formation in Georgia are confined to Richmond and Burke counties, forming a narrow strip along Savannah River north of Griffin's Landing, 16 miles below Shell Bluff, and covering the southern half of Richmond County in and north of the valley of McBean Creek. In general, the formation is too thickly covered by younger strata to have exerted much influence on the topography, but along the streams in the southern part of the area the harder ledges of limestone form prominent bluffs. No irregularities have been detected in the structure of the McBean formation. The upper surface of the formation slopes evenly seaward at the rate of about 10 feet to the mile, and the underlying beds evidently have a slightly steeper dip.

UNDIFFERENTIATED CLAIBORNE DEPOSITS.

The Claiborne deposits in western Georgia are best exposed in the bluff on Chattahoochee River at Fort Gaines and in the Danville Ferry bluff on Flint River, 16½ miles east of Americus. In the intermediate region the formation is thin and poorly exposed. Along Chattahoochee River Langdon[1] distinguished a lower "buhrstone" and an upper calcareous member of the Claiborne, but the division has not been recognized farther east.

Between Flint and Chattahoochee rivers the Claiborne rests upon the Wilcox formation, from which it is separated by an erosion unconformity, which has been observed at Fort Gaines and at Cuthbert. The Claiborne deposits are overlain unconformably by red argillaceous sand of undetermined age, which greatly resembles contiguous beds in the Claiborne and is with difficulty distinguished from them.

DEPOSITS OF JACKSON AGE.

FORMATIONS INCLUDED.

Two formations of Jackson age occur in Georgia—the Barnwell formation, including the Twiggs clay member, and the Ocala limestone, including the Tivola tongue. These are partly equivalent in age but are very different in lithology and present different faunal facies.

The Ocala limestone underlies a large part of Florida and southern Alabama and a considerable area in the southwestern part of Georgia. The Barnwell formation extends from Houston County, Ga., beyond Savannah River an unknown distance into South Carolina.

The Ocala limestone and the Barnwell formation interfinger and merge laterally into each other, but an arbitrary line drawn at the Dooly-Houston county line delimits fairly well the main bodies of the formations. However, the Twiggs clay member of the Barnwell formation extends southward a short distance into the Ocala area and a bed of bryozoan-bearing limestone, which will be referred to as the Tivola tongue of the Ocala limestone, projects as far north as Rich Hill, Crawford County, and forms an important horizon marker near the base of the Barnwell formation in Houston, Twiggs, and adjacent counties.

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[1] Langdon, D. W., Geology of the Coastal Plain of Alabama, pp. 744-745, Alabama Geol. Survey, 1894.

BARNWELL FORMATION.

NAME.

Mr. Vaughan informs the present writers that he made a trip with Mr. Sloan into Barnwell County, S. C., for the special purpose of visiting the type locality of the Barnwell formation, and that he incorporated the results of observations made at that time in the following paragraph in the report by Veatch and Stephenson:[1]

> Mr. Earle Sloan[2] has used the name Barnwell "buhr sands" or Barnwell "phase" for red ferruginous sands that immediately overlie the McBean formation as defined in this report. The type area of the Barnwell sand is in Barnwell County, S. C., where its stratigraphic position is as stated. Sloan, who has also studied the area in Georgia adjacent to Savannah River, states that the Barnwell "phase" is represented by the sands that overlie the fossiliferous marls of Shell Bluff. As there are sands of lower stratigraphic position but very similar in appearance to the Barnwell, Sloan, in several instances, confused the lower horizon with his Barnwell. A notable instance of this confusion is seen in his referring to the Barnwell the fossiliferous sands near Hixon's bridge on Tinker's Creek.[3] The horizon of the fossils of this exposure is far down in the McBean formation. However, it is evident that Sloan intended this name to apply to the red ferruginous sands of the upper horizon and not to those of the lower. He has orally given the information that he has found *Turritella carinata* Lea in the Barnwell sand in Barnwell County, S. C., and he is positive in his opinion that in the type area there is similarity in stratigraphic position and in both lithologic and faunal characters with the fossiliferous red ferruginous sands overlying the McBean formation in Burke County, Ga.

Although no specific locality is mentioned by Sloan in either of his papers cited as the type of his "Barnwell buhr sands," it is evident that he had in mind the higher horizon which "irregularly overlaps the upper margin of the Santee marls."[4]

The stratigraphic succession in western South Carolina, according to Vaughan,[5] is as follows:

> At the base are silicified clays, fuller's earth, the Congaree shales of Sloan; these are overlain by glauconitic sandy marls, locally with silicified shells and buhr rock, and calcareous beds, the Cawcaw shales and marls of Sloan, which are equivalent to his Warley Hill marl, Santee marl, and Mount Hope marl of the Santee area and which are succeeded by calcareous beds containing in their lower portion large numbers of *Ostrea georgiana*, these beds in turn being overlain by red sands, the typical Barnwell buhr sand of Sloan.

Inasmuch as the name Barnwell, as used by Veatch and Stephenson, was restricted to deposits composed almost entirely of sand, they employed the appropriate formational name Barnwell sand. For this is substituted, in the present paper, the name Barnwell formation, which is applied to a less homogeneous composite of materials, including, in addition to the Barnwell sand of Veatch and Stephenson, their so-called "Congaree" clay and the *Ostrea georgiana* zone of their McBean formation.

TWIGGS CLAY MEMBER.

Extensive deposits of fuller's earth grading into calcareous clay of similar properties, which Veatch and Stephenson regarded as forming part of the McBean formation and which they designated the "Congaree clay member of the McBean formation," have been found to occupy a much higher stratigraphic position than the Congaree shales of Sloan in South Carolina, with which they were correlated but which underlie the South Carolina equivalents of the McBean formation, and to be of Jackson age. These deposits are characteristically developed in Twiggs County, and for that reason they are here named Twiggs clay member. Exposures near Pikes Peak station, on the Macon, Dublin & Savannah Railroad, are regarded as typical. The Twiggs clay is treated here as a member of the Barnwell formation.

STRATIGRAPHIC RELATIONS.

In the Mississippi embayment, according to Berry,[6] the last third of Claiborne time was marked by a greater or less emergence of land, which was followed at the beginning of Jackson time by a pronounced transgression of the sea. Similar conditions appear to have prevailed in Georgia east of Flint River. The recession during late Claiborne time in Georgia is more or less conjectural, but the theory of transgression in Jackson time is supported by unequivocal evidence. The Jackson sea crept far inland up the drowned valleys of the old Claiborne land area, across the beveled edges of the lower Eocene and Cretaceous strata, until its waves beat in places upon the crystalline rocks of the Piedmont. The transgression of the sea that took place during Barnwell time appears to have been followed, in eastern Georgia, at least, by a slight emergence of the land which thrust back the Vicksburg shore line. At a subsequent period, perhaps during the Miocene epoch, the sea again advanced but did not attain its former maximum extent.

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[1] Geology of the Coastal Plain of Georgia, p. 285, 1911.

[2] Handbook of South Carolina, pp. 86, 90, Columbia, S. C., Dept. Agr., Commerce, and Immigration, 1917; Catalogue of the mineral localities of South Carolina, pp. 449, 460, South Carolina Geol. Survey, 1908.

[3] Catalogue of the mineral localities of South Carolina, pp. 268, 460.

[4] Handbook of South Carolina, p. 90.

[5] Index to the stratigraphy of North America: U. S. Geol. Survey Prof. Paper 71, p. 737, 1912.

[6] Berry, E. W., Erosion intervals in the Eocene of the Mississippi embayment: U. S. Geol. Survey Prof. Paper 95, p. 82, 1915.

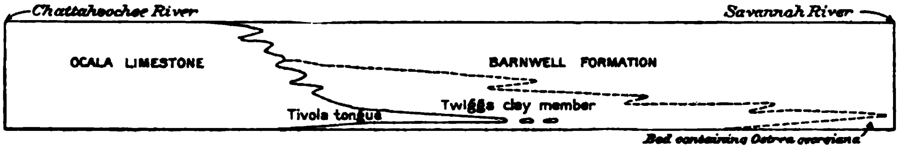

FIGURE 8.—Diagram showing the relations between the Ocala limestone and the Barnwell formation.

The Barnwell formation rests with at least local unconformity upon the McBean formation or, where that is absent, unconformably upon older strata. The relations of the Barnwell formation to the overlying strata are less obvious. On account of the similarity in appearance of much of the Barnwell to younger deposits of various ages, it is in many places difficult to distinguish between them or to be certain of the identity of the overlying formation.

The Twiggs clay member occupies a position at the base and near the landward margin of the Barnwell formation. Although the conditions of deposition were such that the fuller's earth and clays of similar character occur as lenses and discontinuous beds, exposures are abundant in a belt extending from Dooly County to Columbia County, more than halfway across the State. The mode of origin of the Twiggs clay and the agencies that produced its peculiar physical properties are not clearly understood, but its situation indicates that it may have been formed in long, narrow lagoons or bays to which coarse sediments had only occasional access but which appear to have had free communication with the open sea in the southwest, where the clay becomes calcareous and merges into limestones of the Ocala, and in the east, where it merges into marl and oyster-shell beds of the Barnwell formation. Along the northern margin of the outcrops the clay member is overlain with slight unconformity by red sands that apparently belong also to the Barnwell formation. This unconformity is exposed at Pikes Peak and Grovetown, but it evidently represents a withdrawal of the sea for only a short distance and for a short period of time, because farther south the clay member is conformable with the remainder of the Barnwell formation. In the regions north and also east of Wilkinson County, where the Ocala limestone is absent, the clay rests directly upon the surface of the Lower Cretaceous or is separated from it by only a thin bed of sand; at a few places lobes of the clay member overlap the Cretaceous beds entirely and rest upon the crystalline rocks of the Piedmont area. The most notable of these overlaps are at Roberts and Grovetown.

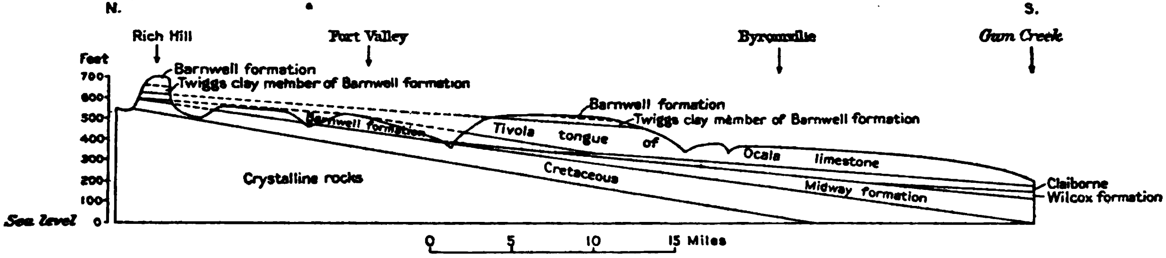

FIGURE 9.—Section from Rich Hill, Crawford County, to the mouth of Gum Creek, Crisp County, Ga.

The Barnwell formation appears to have been laid down at nearly the same time as the Ocala limestone but in a part of the sea supplied more abundantly with sand and mud, and the lateral transition from the siliceous sediments of the Barnwell to the limestones of the Ocala is gradual. The Tivola tongue of the Ocala limestone, which intrudes far into the main area of the Barnwell, represents a temporary invasion of the calcareous phase of deposition beyond its usual limits. The supposed relations between the Barnwell formation and the Ocala limestone are shown in the accompanying diagram (fig. 8) and section (fig. 9).

At the base of the Barnwell formation along Savannah River is a bed of impure limestone or marl that contains large numbers of shells of *Ostrea georgiana* Conrad, a huge oyster, some specimens of which attained a length of nearly 2 feet. This species appears in eastern Georgia to be restricted to the lower part of the Barnwell formation. The *Ostrea georgiana* zone has been traced for miles into South Carolina, and it seems probable that this zone represents a tongue of the Cooper marl of South Carolina and that it is continuous beneath the cover of younger deposits in southeastern Georgia with the Ocala limestone of Georgia and Florida. Local oyster beds that appear to occupy the same stratigraphic position as the bed on Savannah River have been seen as far west as Danville.

LITHOLOGIC CHARACTER.

The greater part of the Barnwell formation is sandy, comprising widespread deposits of coarse brilliant-red sand which appears to derive its color from weathered glauconite, together with locally indurated beds of gray sandstone which in places approaches quartzite in texture, and basal conglomerates resembling the gravels of the Pleistocene terraces. The sand in many localities incloses masses of flint, many of which are fossiliferous and appear to represent the silicified remnants of limestone lenses. Some of the flint is in scattered lumps, but most of it is restricted to well-defined zones.

The Twiggs clay member of the Barnwell consists typically of greenish-gray siliceous clay of low specific gravity, not plastic but breaking with a hackly fracture and exhibiting all the properties of fuller's earth. The fuller's earth grades laterally into calcareous clay of similar appearance and properties and thence into argillaceous limestone. Some of the clay is free from grit, but most of it is interbedded with thin layers of sand.

At places where the fuller's earth was not deposited and north of the limit of clay deposition beds of yellowish-green glauconitic sand extend to the base of the Barnwell formation. Near the base of the formation are local beds of lignite, shaly aluminous sandstone, quartzite, and completely silicified sandy limestone.

THICKNESS.

In eastern Georgia the thickness of the Barnwell formation has not been accurately determined, because the contact with the overlying formations is uncertain. In the Shell Bluff section 65 feet belong to this formation. At Louisville, which is about 10 miles from the Cretaceous-Barnwell contact, 100 feet of beds referred to the Barnwell formation are exposed from Rocky Comfort Creek up to the level of the town. In a deep well near Louisville the top of the Cretaceous is thought to have been reached at a depth of about 350 feet,[1] but this thickness probably includes some Claiborne strata in addition to the Barnwell formation. The available evidence does not indicate a thickness greater than 200 feet for the Barnwell formation in eastern Georgia, and it may be considerably less.

In Twiggs County the beds referred to the Barnwell formation extend from the surface of the Lower Cretaceous in the Dry Branch kaolin mines, at an altitude of 400 feet above sea level, to the tops of the higher hills in the vicinity of Pikes Peak, at an altitude of 625 feet. The formation is little more than 200 feet thick.

In Houston County, as the Tivola tongue of the Ocala limestone thickens the Barnwell formation becomes thinner, and only about 100 feet of the Ross Hill section may be referred to it.

The Twiggs clay member attains its maximum thickness near Pikes Peak in Twiggs County, where fuller's earth occurs at two distinct horizons separated by a bed of greenish fossiliferous sand, the whole being 100 feet thick. In Houston County the 100 feet of fuller's earth, calcareous clay, and sand of the Barnwell formation may be considered as belonging almost entirely to the Twiggs clay member. South of these counties the clay becomes thinner as the underlying Tivola tongue of the Ocala limestone thickens. To the northeast, also, the Twiggs clay becomes thinner along the strike, and at few places in Jefferson and Columbia counties is it as thick as 20 feet.

PALEONTOLOGIC CHARACTER.

The fauna of the Barnwell formation has already been discussed at some length (pp. 42–49). In general terms, it is an assemblage of shallow-water or littoral species which inherited many elements from the preceding upper Claiborne or Gosport fauna but which includes a number of species not known from older deposits.

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[1] McCallie, S. W., A preliminary report on the underground waters of Georgia: Georgia Geol. Survey Bull. 15, p. 129, 1908.

The Mollusca constitute the dominant element, being represented by numerous genera and species. Bryozoa are abundant in what may be regarded as transition beds between the Barnwell and laterally adjacent formations but are scarce in more typical deposits. Corals are represented by a few very prolific species, and echinoderms by *Periarchus pileus-sinensis* and *Mortonella quinquefaria*. The most significant vertebrate thus far discovered is the huge zeuglodon *Basilosaurus cetoides*, which is particularly valuable as a guide fossil.

The Twiggs clay member of the Barnwell formation has yielded a small flora which assists in correlating isolated exposures of the formation with one another but which presents inconclusive evidence for determining the age of the deposits because the floras of the upper Claiborne and lower Jackson are very similar. As originally described by Berry,[1] the flora included only 17 species of plants, all of them new, but recent collections have increased the total to 26, and most of them have since been discovered elsewhere. The following list with comments has been furnished by Prof. Berry:

Flora of the Twiggs clay member of the Barnwell formation.

	Wilcox group.	Yegua formation.	Lisbon formation.	Gosport sand.	Jackson formation.
Acrostichum georgianum	....	....	×	×	....
Arundo pseudogoepperti	....	×	×	×	×
Carpolithus najasoides	....	....	....	....	....
Castanea clairbornensis	....	....	....	....	....
Cassia georgiana	....	....	....	....	....
Conocarpus eocenica	....	....	....	×	×
Cupanites nigricans[a]	....	....	....	....	....
Cinnamomum augustum	....	....	×	....	....
Dodonaea viscosoides	....	×	×	....	×
Ficus claibornensis	....	....	....	....	....
Ficus newtoneusis	....	....	×	....	....
Malapoenna sp	....	....	....	....	....
Mimosites georgianus	....	×	×	....	....
Momisia americana	....	×	....	....	....
Pestalozzites minor	....	....	....	....	....
Pisonia claibornensis	....	×	....	....	....
Pistia claibornensis	....	....	....	....	....
Pteris inquirenda	....	....	×	....	....
Potamogeton megaphyllus	....	....	....	....	....
Rhizophora eocenica	....	....	....	....	....
Sapindus georgiana	....	×	×	....	....
Sophora claiborneana	....	....	×	....	×
Sophora wilcoxiana	×	×	....	....	....
Sphaerites claibornensis	....	....	....	....	....
Terminalia phaeocarpoides	....	....	....	....	×
Thrinax eocenica	....	×	×	....	....

[a] Green River formation of Wyoming.

To summarize this list, it may be noted that of the 26 species found in Georgia 1 comes up from the Wilcox, 3 occur in the St. Maurice, 8 occur in the Yegua, 10 in the Lisbon, and 3 in the Gosport, making 13 of the 26 that occur in known Claiborne. One additional species occurs in the Green River of Wyoming.

Six of the Georgia species occur in the Jackson. Although the Twiggs clay flora is thus apparently more like the Claiborne flora of other areas than it is like the Jackson, two features make this similarity more apparent than real. One is the fact that the continental deposits in Texas referred to the Yegua, in which several of the Georgia species reappear, are believed by me to be of Jackson age. The second modifying factor is that the bulk of the known Claiborne flora is found in the upper Claiborne and that this upper Claiborne flora is but slightly modified in passing over into the Jackson.

It should not be overlooked that 10 species, or 38 per cent of the total number, have not yet been found elsewhere and that subsequent collecting may change the relative proportions of Claiborne and Jackson species. The 26 species of plants known to science out of the hundreds that must have existed at the same time form so insignificant a part of the flora that they ought not to be considered as necessarily representative of the whole. Moreover, as pointed out by Ulrich,[2] paleobotanists are prone to place disputed formations lower in the time scale than is indicated by the marine invertebrates, because the plants attain their greatest development during the emergent interval preceding the introduction of the new marine fauna.

AREAL DISTRIBUTION.

The Barnwell formation extends in a broad belt from Savannah River nearly to Flint River, but in the western half of this belt, the area lying west of Oconee River, the formation is intermediate in character between the typical Barnwell and the Ocala limestone, merging into the Ocala toward the south, or seaward, and toward the southwest. In the description by counties the southwestern boundary of the formation is arbitrarily placed at the Houston-Dooly county line, although the Twiggs clay member and perhaps also some of the overlying red sands extend for some distance south of this line, and a wedge of bryozoan-bearing limestone (the Tivola tongue of the Ocala limestone) projects into the Barnwell formation in Houston, Twiggs, and adjacent counties, and forms an important horizon marker near the base of the formation. (See map, Pl. VII, and section, fig. 8.)

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[1] Berry, E. W., The Upper Cretaceous and Eocene floras of South Carolina and Georgia: U. S. Geol. Survey Prof. Paper 84, p. 129, 1914.

[2] Ulrich, E. O., Correlation by displacements of the strand line and the function and proper use of fossils in correlation: Geol. Soc. America Bull., vol. 27, p. 465, 1916.

The Barnwell formation occupies considerable areas in Burke, Richmond, Jefferson, Glascock, Washington, Wilkinson, Twiggs, and Houston counties and smaller parts of adjacent counties. The northern boundary is very irregular, the plain forming the surface of the formation having been deeply dissected by streams that have cut their valleys down into the Cretaceous strata, leaving promontories and erosional outliers of the Barnwell in the interstream areas. The southern boundary is likewise irregular, but in reverse order, having long salients extending down the river valleys.

The Twiggs clay member in eastern Georgia is confined chiefly to the northern edge of the area occupied by the Barnwell formation, but toward the west its outcrop widens until it practically coincides with that of the formation as a whole. It is characteristically developed near Grovetown, Columbia County, and outcrops have been noted at short intervals from that locality to Rich Hill, in Crawford County.

PHYSIOGRAPHIC EXPRESSION.

The unconsolidated sands of the Barnwell formation have yielded readily to erosional agencies and, especially along the fall line, have been deeply trenched. The harder sandstones have resisted better and in a few places, as at Browns Mountain, form hills of considerable height. In most places the Twiggs clay member is overlain by beds of sand, but where not so protected it shows a tendency to form barren "washes" or grassy slopes.

STRUCTURE.

The Barnwell formation strikes approximately northeastward.

From exposures along the Macon-Perry road (National Highway) in Houston County the slope of the Cretaceous surface is estimated at more than 12 feet but not more than 20 feet to the mile. The dip of the Barnwell formation is a little less than that of the surface upon which it lies and is probably about 10 feet to the mile.

In Twiggs County the slope of the upland plain is 9 feet to the mile measured parallel to the Macon, Dublin & Savannah Railroad from Pikes Peak to Danville (southeast). The dip of the Barnwell formation, which is a little steeper than the slope of the plain, is probably between 10 and 15 feet to the mile.

In the eastern part of the State the upper surface of the Lower Cretaceous beds is very irregular, and the dip can not be stated with certainty. The base of the Barnwell formation in this region slopes from 500 feet above sea level at Grovetown to 80 feet at Griffin's Landing, a fall of 420 feet in 36 miles, or a little more than 11 feet to the mile toward the southeast.

Except for the slight tilt toward the southeast the beds of the Barnwell formation are practically undisturbed. The only indication of later movements detected is a local anticline, cut through by the railroad at Pikes Peak, in which the limbs dip 4° SE. and 3° NW.

OCALA LIMESTONE.

NAME.

In 1892 Dall[1] applied the name Ocala to limestone deposits exposed in the vicinity of Ocala, Marion County, Fla., and some years later the same author described a number of species of mollusks from the Ocala limestone and published a partial list of the species found in it.[2] This fauna was first recognized in Georgia by Vaughan,[3] who correlated the outcrops of limestone in Flint River near Bainbridge with the Ocala "zone," and the name Ocala limestone was recently employed by Cooke[4] in referring to the same deposits.

The Ocala limestone as defined in this report includes the greater part of the Vicksburg formation of Veatch and Stephenson[5] as well as most of the Jackson formation of the same authors. The Tivola tongue of the Ocala limestone is typically exposed at the quarry of the Planters Limestone Co., 2 miles south of Tivola. (See p. 76.)

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[1] Dall, W. H., Correlation papers—Neocene: U. S. Geol. Survey Bull. 84, p. 103, 1892.

[2] Dall, W. H., Contributions to the Tertiary fauna of Florida, pt. 6: Wagner Inst. Trans., vol. 3, pp. 1219–1654, 1903.

[3] Vaughan, T. W., A Tertiary coral reef near Bainbridge, Ga.: Science, new ser., vol. 12, p. 873, 1900; The Eocene and lower Oligocene coral faunas of the United States: U. S. Geol. Survey Mon. 39, p. 31, 1900.

[4] Cooke, C. W., The age of the Ocala limestone: U. S. Geol. Survey Prof. Paper 95, p. 110, 1915; The stratigraphic position and faunal associates of the orbitoid Foraminifera of the genus *Orthophragmina* from Georgia and Florida: U. S. Geol. Survey Prof. Paper 108, pp. 109–113, 1917 (Prof. Paper 108–G).

[5] Veatch, Otto, and Stephenson, L. W., op. cit., pp. 296–362.

STRATIGRAPHIC RELATIONS.

The relations of the Ocala limestone to both the underlying and the overlying formations are imperfectly known. At its northeastern limits the formation overlaps upon older strata (see fig. 8, p. 53), and similar conditions may prevail toward the west, but whether the overlap extends all the way to Chattahoochee River is uncertain. At any rate, the Claiborne deposits are not completely overlapped in the west, as in central Georgia.

The Ocala limestone is overlain by the Vicksburg formation, but the Vicksburg has been eroded so much that its original relations to the Ocala are very obscure. Where the two formations have been observed in contact no evidence of physical break in sedimentation between them has been detected. In the vicinity of Bainbridge the upper surface of the Ocala is exceedingly irregular, having suffered considerably from degradational agencies, but how much this unevenness is due to solution and disintegration of comparatively recent date or to what extent it antedates the deposition of the overlying beds is at present unknown. The Vicksburg in this region is apparently represented mostly by scattered lumps of residual flint, the main overlying formation belonging to the Apalachicola group. The following note is introduced through the courtesy of Messrs. Vaughan and Bassler:

> In 1915 Vaughan [1] pointed out that a species of coral referred to by him as *Orbicella cellulosa* (Duncan) is common to Vicksburg deposits at Vicksburg, Miss., to the basal Chattahoochee at Bainbridge, Ga., to the Tampa formation at Tampa, Fla., and to the Antigua formation of Antigua. Recent unpublished results obtained by Vaughan from his studies of the corals and associated organisms in the base of the Chattahoochee formation and in the Antigua formation of Antigua indicate that these deposits are of middle Oligocene age and that they are stratigraphically only a little above the upper Vicksburgian Byram calcareous marl [2] of Mississippi. Bassler has identified Bryozoa characteristic of the Marianna limestone (middle Vicksburgian) in chert found associated with the coralliferous chert in the vicinity of Bainbridge but not in the same chert masses as the corals. As the Bryozoa and the corals have not been found together, they seem to represent different horizons. A considerable number of mollusks occurring also at Vicksburg have been listed from these beds by Dall,[3] but a critical comparison of the faunas has not been attempted.

The Ocala limestone appears to have been deposited almost contemporaneously with the Barnwell formation, with which it is interbedded in the transition area. The Tivola tongue, which extends for many miles into the area occupied by the Barnwell, lies beneath the larger mass of that formation, but in most places is underlain by thin sandy beds that are classed with the Barnwell.

LITHOLOGIC CHARACTER.

The Ocala limestone consists chiefly of soft white or cream-colored limestone that in places is composed almost entirely of the remains of Foraminifera and Bryozoa. The lower portion is more arenaceous and in places approaches sandstone in composition. In the transition area at the northeastern extremity of the formation the Ocala becomes highly argillaceous and merges into the Twiggs clay member of the Barnwell formation.

On exposed surfaces at many localities the pores of the soft limestone have been filled up by infiltration of calcium carbonate, which has "case hardened" the outer layers of the rock into hard semicrystalline limestone. That processes of silicification have been active in certain regions is shown by large masses of white flint or silicified limestone that are strewn over the surface or embedded in residual sand, but such action has by no means been confined to the Ocala limestone, as it has attacked the Vicksburg and Chattahoochee limestones as well.

THICKNESS.

Reliable data concerning the thickness of the Ocala limestone are lacking. In a well at Albany [4] the drill is believed to have entered the Claiborne at a depth of about 280 feet, and the total thickness of the Ocala in this vicinity probably does not greatly exceed 300 feet. At Bainbridge the drill penetrated 750 feet of limestone, but how much of this is of Jackson age is unknown. The Tivola tongue in few places exceeds 40 feet in thickness and is commonly much thinner.

PALEONTOLOGIC CHARACTER.

The Ocala limestone contains a large and characteristic bryozoan fauna, of which about 90 species have been found in Georgia.[5]

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[1] Carnegie Inst. Washington Year Book 13, p. 360, 1915.

[2] Defined by C. Wythe Cooke in Correlation of the deposits of Jackson and Vicksburg ages in Mississippi and Alabama: Washington Acad. Sci. Jour., vol. 8, pp. 186-198, 1918.

[3] Dall, W. H., A contribution to the invertebrate fauna of the Oligocene beds of Flint River, Ga.: U. S. Nat. Mus. Proc., vol. 51, pp. 488-489, 1916.

[4] Georgia Geol. Survey Bull. 26, pp. 317-318, 1911.

[5] Canu, Ferdinand, and Bassler, R. S., manuscript list.

Foraminifera are exceedingly abundant and in places constitute a large part of the rock, but lists are not yet available. The orbitoid Foraminifera are abundant, being represented by several species of *Orthophragmina*, both smooth and stellately marked, and also by species of *Lepidocyclina*. Species of both genera have been erroneously referred to *Orbitoides mantelli*, which is the type species of the genus *Lepidocyclina* and appears to be peculiar to the horizon of the Vicksburg represented by the Marianna limestone. *Operculina* is common in the middle or lower part of the formation.

Echinodermata attained during Ocala time a greater development than during any other part of the Tertiary period in the Atlantic and Gulf Coastal Plain area. These forms appear to be very much restricted in vertical range, and it seems probable that more detailed work will result in the discrimination of several zones by means of them. *Periarchus pileus-sinensis* appears to be restricted to the Tivola horizon; other species, which occur higher in the formation, are *Cidaris georgiana, Laganum? crustuloides, Schizaster floridanus, Macropneustes mortoni, Cassidulus (Rhynchopygus) depressus, Cassidulus (Pygorhynchus) conradi, Cassidulus (Pygorhynchus) georgiensis, Eupatagus carolinensis, Oliogopygus haldermani*, and *Agassizia conradi.*

A rather extensive molluscan fauna is contained in the Ocala limestone, but comparatively few forms have been preserved well enough for determination. A noteworthy exception to this is found in the pectens, which occur in great abundance and are beautifully preserved. *Pecten perplanus*, a typically Jackson species, is present, together with several closely related species or varieties. *Amusium ocalanum*, originally described from Florida, is widely distributed in Georgia.

AREAL DISTRIBUTION.

The Ocala limestone occurs at or near the surface over a broad belt lying chiefly in the drainage basins of Chattahoochee and Flint rivers. (See geologic map, Pl. VII.) The belt crosses Chattahoochee River between Saffold and a point about 4 miles above the mouth of Flint River, an airline distance of nearly 30 miles; thence it extends northeastward to the Dooly-Houston county line, but at that extremity the Ocala is interbedded with or transitional to the Barnwell formation. Northeast of this line the lower portion of the formation, the Tivola tongue, extends into the Barnwell area through Houston, Twiggs, and Bleckley counties, and parts of Wilkinson and Crawford counties. Throughout much of its areal extent the formation is concealed from view by a thin cover of younger strata, mainly sands, but it is exposed along watercourses, and its presence in the interstream areas is indicated by lime sinks and flint boulders.

PHYSIOGRAPHIC EXPRESSION.

The ready solubility of the Ocala limestone has assisted in the degradation of its surface. In the region lying between Flint and Chattahoochee rivers underground solution has been extensive, and the plain is dotted with lime sinks and ponds, ranging from shallow saucer-shaped circular depressions to sinks of considerable size. The region is a flat low-lying plain, in marked contrast to the high sandy plateau upheld by the Alum Bluff formation east of Flint River. Small surface streams are not abundant, much of the drainage going through subterranean channels.

In the northeastern part of the area occupied by the Ocala limestone, solution appears to have played a part in the formation of topographic forms subordinate to that of mechanical agencies. The harder limestone ledges have resisted erosion better than the clay deposits with which they are interbedded, with the result that the limestone stands out in steep slopes or bluffs.

STRUCTURE.

The Ocala limestone has not been studied in sufficient detail to permit accurate determination of its structure, and the scarcity of recognized horizon markers makes such determination difficult. The formation as a whole appears to be inclined very gently seaward at the rate of probably 10 feet to the mile. Gentle flexures may exist, but none have been detected.

ECONOMIC GEOLOGY.

The greater part of the workable limestones and marl deposits of the Coastal Plain of Georgia pertain to the Ocala limestone. These have been treated in detail by Brantly.[1]

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[1] Brantly, J. E., Georgia Geol. Survey Bull. 21, 1916.

SUMMARY.

The differences between the interpretation of the stratigraphy of Georgia here offered and that of Veatch and Stephenson may be briefly summarized as follows:

The deposits of Claiborne age, which they mapped as extending uninterruptedly across the entire width of the State, have been restricted to two areas, one along Savannah River and McBean Creek and the other between Flint and Chattahoochee rivers. The deposits of Claiborne age in the east retain the name McBean formation, but those in the west are called undifferentiated Claiborne.

The Barnwell sand, which they regarded as of upper Claiborne age, is raised in the time scale and placed in the Jackson epoch with the name altered to Barnwell formation. The so-called "Congaree clay member of the McBean formation" is placed bodily in the Barnwell formation and, together with calcareous clays which were already correlated with the Jackson formation, is renamed Twiggs clay member, the name Congaree being inappropriate because the clay is now known to be much younger than the typical Congaree shales of Sloan. Those parts of their McBean formation left after the elimination of the undifferentiated Claiborne and the typical McBean formation are here included in the Barnwell formation.

The littoral facies of the Barnwell fauna bears an exceedingly close relationship to the littoral fauna of the Gosport sand of Alabama but is transitional between that fauna and typical Jackson faunas and contains enough distinctive species to justify the reference of it to the Jackson epoch. The discovery of evidence of an extensive transgression of the sea upon the old land surface at the beginning of Barnwell time corroborates the reference of the formation to the beginning of a new stage rather than to the closing period of an old.

The greater portion of the Vicksburg formation of Veatch and Stephenson is transferred to the Jackson epoch, under the name Ocala limestone, and the Jackson formation of their usage is divided between the Ocala limestone and the Barnwell formation. The residue of the Vicksburg formation is left untouched for the present.

LOCAL DETAILS.

McBEAN FORMATION.

McBean.—Several sections along the south side of McBean Creek, southeast of McBean station, are given by Vaughan,[1] and localities farther upstream are described by Brantly.[2] These descriptions show that the McBean formation is variable within short distances. East of the Central of Georgia Railway the formation consists largely of sand, clay, and lignitic material, with marl only near the base of the section. West of the railway the marl beds become much thicker, reaching a thickness of over 50 feet, all above creek level, on the Newton Palmer property. The two following sections are typical of the beds east and west of the railway:

Section on Newton Palmer property, McBean Creek, on west side of Central of Georgia Railway.

[Measured by J. E. Brantly, op. cit., p. 46.]

	Feet.
Barnwell formation (?):	
6. Concealed interval; sandy soil on top of hill	34
McBean formation:	
5. Soft white argillaceous "rotten" limestone	7
4. Medium hard highly fossiliferous limestone; fossils poorly preserved	2
3. Soft, "rotten" to consolidated cream-colored argillaceous limestone	45
2. Blue glauconitic clay like fuller's earth	6
1. Hard arenaceous fossiliferous limestone	2
Creek bed.	
	96

Section in gully on south side of McBean Creek, a quarter of a mile east of the bridge on the Augusta-Savannah public road.

[Measured by C. W. Cooke.]

	Feet.
Barnwell formation (?):	
6. Brilliant red massive argillaceous sand, very coarse in lower portion	20
McBean formation:	
5. Coarse incoherent yellow sand; at the top a locally indurated ledge of friable white sandstone, which elsewhere is represented by carbonaceous sand	30
4. Coarse quartz sand in a matrix of greenish-yellow clay	4
3. Fine yellow sand, incoherent at top, argillaceous below, with patches of calcareous and carbonaceous, almost lignitic material	5
2. Soft fine-grained sandy gray calcareous marl, with a few fragments of shells and some hard nodules	3
1. Concealed interval to creek level, about	30
	92

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[1] Veatch, Otto, and Stephenson, L. W., op. cit., p. 242.

[2] Brantly, J. E., Report on the limestones and marls of the Coastal Plain of Georgia: Georgia Geol. Survey Bull. 21, pp. 44-50, 1916.

In the bottom of the gully at the second locality were found a few fragments of fossiliferous chert that were probably derived from the red sand, bed 6 of the section. The relations of the upper bed to bed 5 are somewhat obscure, but it seems probable that there is an erosional unconformity between them.

On the Waynesboro road, at the foot of the hill leading down to McBean Creek, a few fragments of shells were seen in yellow sand, apparently bed 3 of the preceding section. The shells are not disseminated throughout the sand but are segregated into small patches of shell marl. This is probably the horizon from which Sloan obtained the large collection of fossils listed on pages 50–51.

Silver Bluff.—The southernmost exposure of the Lower Cretaceous beds and the best section of the lower part of the McBean formation is seen at Silver Bluff, 27 miles by river below Augusta and 12 miles above Shell Bluff.

Section at Silver Bluff, Savannah River.

[Described by H. K. Shearer. Measured at west end of bluff on South Carolina side.]

	Feet.
Recent:	
8. Soil; gray sandy loam	2
Eocene—McBean formation:	
7. Coarse mottled argillaceous sand	6
6. Lenticular mass of crumbly, sandy iron-stained clay, somewhat like fuller's earth. Maximum thickness	6
5. Coarse red and yellow cross-bedded sand	10
4. Layer of sand cemented by limonite	.1
Unconformity.	
Lower Cretaceous:	
3. Laminated yellow and brown sandy clay, maximum	2
2. Blue highly plastic clay free from grit	2.5
1. Yellow-gray arenaceous clay	2.5
	31.1

The strata classed as Lower Cretaceous were slightly folded prior to the deposition of the overlying material, but there is no evidence elsewhere of any considerable disturbance of the beds. The beds above the unconformity are believed to lie at the same horizon or a little lower than the marl beds of Claiborne age at Shell Bluff, but as they were deposited very near the shore line they contain no calcareous material. If the correlation of these beds is correct, the Cretaceous surface dips beneath the river level near the mouth of McBean Creek.

Shell Bluff.—Shell Bluff, on Savannah River, 163 miles from the mouth of the river, is one of the classic localities in the study of the geology of the Coastal Plain of Georgia and South Carolina and has been described by many geologists during the last century. The 140 to 150 feet of beds exposed there have previously been correlated with various formations from the Claiborne to the Vicksburg. In the report on the geology of the Coastal Plain of Georgia the whole series was referred to the Claiborne group, and the line of division between the McBean formation and the Barnwell sand was placed at the top of the *Ostrea georgiana* zone. However, Vaughan[1] says in that report:

> The McBean formation includes two paleontologic horizons. The lower one * * * is especially characterized by *Pleurotoma nodocarinata* Gabb, *Turritella nasuta* Gabb, *Turitella nasuta* var. *houstonia* Harris, *Ostrea sellaeformis* Conrad, *Pteropsis lapidosa* Conrad, and *Corbula fossata* Meyer and Aldrich.
>
> A higher horizon is represented especially well along Savannah River, between Shell Bluff, upstream, and Griffin's Landing, downstream. Along this stretch of the river a prominent ledge, largely composed of *Ostrea georgiana* Conrad, forms the top of the McBean formation. Although this formation could be subdivided along Savannah River, it was found impracticable to extend the subdivision westward, for which reason the *Ostrea georgiana* bed is considered as constituting its upper portion.

The red sand overlying the *Ostrea georgiana* zone was called the Barnwell sand, which was then supposed to be of Claiborne age. Since the publication of the Coastal Plain report, however, R. S. Bassler[2] has identified Bryozoa characteristic of the Jackson deposits from the *Ostrea georgiana* zone, and careful stratigraphic work has resulted in the recognition of this horizon in the Barnwell formation at numerous localities in central Georgia.

The following generalized section at Shell Bluff is made up from the writers' notes and from sections previously published.[3] The *Ostrea georgiana* zone occurs only downstream from the boat landing, but the underlying beds are exposed in the steep part of the bluff above the landing.

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[1] Georgia Geol. Survey Bull. 26, p. 240, 1911.

[2] Oral communication.

[3] For more detailed sections see Sloan, Earle, Catalogue of the mineral localities of South Carolina: South Carolina Geol. Survey, 4th ser., Bull. 2, pp. 271–272, 1908. Veatch, Otto, and Stephenson, L. W., Georgia Geol. Survey Bull. 26, pp. 243–247, 1911. Brantly, J. E., Georgia Geol. Survey Bull. 21, p. 51, 1916.

Generalized section at Shell Bluff.

Barnwell formation:	Feet.
7. Apparently all red argillaceous sand to level of upland plain. The surface of the plain is covered by several feet of loose gray sand, but clayey sand for road building is obtained from shallow trenches along the roads	35
6. *Ostrea georgiana* zone. The base of the oyster bed is 80 feet above zero water level in the river, and although exposures are not continuous, oysters are found up to 110 feet above water level. The oyster ledge at the base of the zone contains very large shells in a matrix of yellowish sand. Above this is a bed of calcareous conglomerate containing quartz pebbles. Above the conglomerate bed the oysters are in a matrix of yellowish marl or hard calcareous clay, having some of the characteristics of fuller's earth. The matrix of the oyster shells contains Bryozoa of the Rich Hill facies of the Jackson fauna	30
McBean formation:	
5. Concealed interval between the upper and lower bluffs. Covered by talus from the *Ostrea georgiana* zone and other overlying formations but probably is a bed of sand	10
4. Moderately hard to hard light-colored marl, with few fossils	9
3. Ledge of hard brown coquina-like rock, with numerous hollow casts of fossils	6
2. White to purplish sandy limestone, made up largely of fossils. This is the most important fossiliferous stratum of the McBean formation, and Vaughan collected from it a total of 35 species. It is characterized by large specimens of *Ostrea sellaeformis*	6
1. Sandy and argillaceous marl, not abundantly fossiliferous; in layers differing considerably in color, hardness, and chemical composition. A number of analyses show calcium carbonate content ranging from 50 to 90 per cent, but the actual local variation is even greater, for there are thin ledges of comparatively pure limestone and other beds of slightly calcareous sand and clay. The color, as a whole, appears light gray, but individual beds have various shades of white, yellow, buff, gray, and greenish yellow. This bed is exposed as an almost vertical cliff, rising from water level, in which the harder layers form projecting ledges	50

The 99-foot bench mark of the United States Army Engineers is situated near the base of the bluff, and low-water level in the river is reported to be 87 feet above sea level. The preceding section starts approximately 90 feet above sea level and extends to an altitude of 235 feet, with the base of the Barnwell at 170 feet.

On Savannah River downstream from Shell Bluff marl of the McBean formation is exposed at Demerie's Ferry, Hancock Landing, Utley Point, and Blue Bluff and finally passes beneath water level at Griffin's Landing, where it is overlain unconformably by the *Ostrea georgiana* zone and calcareous fuller's earth.

UNDIFFERENTIATED CLAIBORNE DEPOSITS.

Fort Gaines.—A complete section of the Wilcox and Claiborne formations is exposed in a high bluff along the Georgia side of Chattahoochee River at Fort Gaines and in the slopes from the terrace on which the town is built up to the level of the upland plain. The sections given below show the character of the Claiborne in this vicinity.

Section along road leading east from the Raymur Hotel, Fort Gaines.

[Thicknesses approximate. Measured by L. W. Stephenson,[1] with comments by H. K. Shearer.]

Age unknown:	Feet.
8. Coarse red ferruginous pebbly sand. (Similar material extends down the hill for some distance, probably creep.) Thickness to top of hill, half a mile from the hotel	50
Eocene: Undifferentiated Claiborne:	
7. Greenish sandy clays and argillaceous sands, more or less weathered and mottled	40
6. Compact fine greenish-gray sandstone, with fossil prints (fossils collected)	3
5. Pale-green fine loose sand	3
4. Compact fine greenish-gray sandstone, with fossil prints (fossils collected)	3
3. Light-green compact, finely arenaceous clay. A part of the bed is indurated, breaks with hackly fracture, and resembles the silicified fuller's earth of eastern Georgia	7
2. Fine green sandstone	3
1. Greenish clays and sands, more or less weathered and mottled	65
	175

The following fossil mollusks from beds 4 and 6 were identified by T. W. Vaughan:

Plejona sp.
Turritella sp.
Leda pharcida Dall?
Venericardia planicosta Lamarck.
Miltha claibornensis (Conrad).
Cytherea sp.
Solen lisbonensis Aldrich?

The preceding section starts at an altitude of 225 feet above sea level, 15 feet below the level of the business section of Fort Gaines, which is on the second (upper) river terrace. The following section is exposed in the bluff a quarter of a mile below the wagon bridge and

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[1] Georgia Geol. Survey Bull. 26, p. 263, 1911.

has its top at the edge of the terrace, at an altitude of 215 feet above sea level.

Section of bluff at Fort Gaines.

[Measured by Otto Veatch; descriptions revised by H. K. Shearer.]

	Feet.
Pleistocene:	
9. Coarse red sand with pebbles in the lower half; caps the bluff	15
Eocene:	
Undifferentiated Claiborne:	
8. Drab fine-grained laminated clay with sand partings; has the appearance of fuller's earth but is not nearly so light and porous as the Twiggs clay, of Jackson age, and apparently has a more kaolinic base	8
7. Yellow and grayish glauconitic sand. Locally it is oxidized and contains limonite-cemented crusts	10–12
6. Clay and sand, in part calcareous; consists of drab carbonaceous clay at base, sand in middle, and very sandy shell marl at the top	20
5. Indurated clay layer or drab claystone; contains fossils and is similar lithologically to the claystone east of the town of Fort Gaines. (See preceding section)	2–2.5
4. Grayish argillaceous sand	6
3. Yellowish and gray quartz sand; contains calcareous sand nodules; small pebbles noted at the base; fossils *Xenophora*, *Venericardia planicosta*	2–2.5
Unconformity (?).	
Wilcox formation:	
2. Clay, in part carbonaceous; calcareous, and lignitic sand, etc	39
Unconformity.	
Midway formation:	
1. Impure limestone, maximum	20
	124

In this section the Claiborne beds occupy the interval from 150 to 200 feet above sea level, and in the preceding section they extend from 225 to 350 feet, indicating a total thickness of 200 feet, only 25 feet of which is concealed. The top of the Claiborne has not been accurately located at this place, but on the Edison road, half a mile southeast of Fort Gaines, the Claiborne is overlain unconformably by sand interbedded with purple and white mottled plastic clay at an altitude of 355 feet above sea level.

The Claiborne strata are exceedingly variable in composition in the vicinity of Fort Gaines, and their lithologic appearance at the town is completely unlike that a mile away. This difference is shown at a locality on the Lower River Road, three-quarters of a mile south of Fort Gaines, where there is an exposure of 85 feet of drab clay which is in part massive and sandy, in part interlaminated with sand, and is not fossiliferous. The clay crops out between 180 and 265 feet above sea level and is thought to be of Claiborne age.

Cuthbert.—In the cuts on the Central of Georgia Railway west of Cuthbert two unconformities, believed to mark the top and bottom of the Claiborne, are exposed. The lower unconformity, at an altitude of 410 feet above sea level, is seen near the 121-mile post, 3 miles west of Cuthbert.

Section 3 miles west of Cuthbert, near 121-mile post, Central of Georgia Railway.

	Feet.
Undifferentiated Claiborne:	
5. Dark-red argillaceous sand with a few clay laminae	14
4. Fine gravel	1
Unconformity.	
Wilcox formation:	
3. Light-colored argillaceous sand, with laminae and beds 2 or 3 feet thick of clay like fuller's earth	10
2. Red argillaceous sand, with clay laminae	30
1. Blue and gray banded clay, with some sand laminae, dense, approaching kaolin rather than fuller's earth in properties	30
	85

A second unconformity is exposed 1 mile farther east, in the cut near the 120-mile post, at an altitude of 460 feet.

Section 2 miles west of Cuthbert, near 120-mile post, Central of Georgia Railway.

Oligocene: Undifferentiated Vicksburg:	
2. Yellow plastic clay, partly laminated but with bedding much distorted by slump. Distributed through the clay are boulders and irregular masses of chert, containing fossils, most of which are undeterminable, but the Vicksburg species *Pecten poulsoni* was recognized	10+
Unconformity. (The unconformity is very irregular within a vertical range of 5 feet and is marked locally by a layer of ferruginous sandstone 1 to 2 inches thick, or by a thin band of carbonaceous sand or clay.)	
Eocene: Undifferentiated Claiborne:	
1. Brown to yellow and red sand, a glauconitic sand more or less weathered, with local masses cemented by limonite	5+

Exposures between the two cuts show that the entire 50 feet of beds of the Claiborne consist of red sand, with only a few laminae of clay.

BARNWELL FORMATION.

BURKE COUNTY.

The Barnwell formation in Burke County consists of calcareous clay and shell marl overlain by red sand containing ledges of fossiliferous chert. The *Ostrea georgiana* zone, which is characteristically developed at Shell Bluff (see pp. 60–61) and other localities on Savannah River, has been recognized also at several places in the interior. At Keys Mill, on Brushy Creek, in the northwest corner of Burke County, 3 miles northwest of St. Clair, a bed of *Ostrea georgiana* similar to that at Shell Bluff and apparently occurring at the same stratigraphic horizon is exposed in an excavation near the mill dam. The section at this locality follows.

Section at Keys Mill.

Barnwell formation:	Feet.
5. Red argillaceous sand containing laminae of yellow plastic clay near the base and quartz gravel beds and a few fragments of chert near the top	40
4. Coarse yellow sand, carbonaceous at the base	10
3. Pale-green, somewhat calcareous hackly clay or fuller's earth containing thin beds and irregular pockets of sand. The contact with the oyster bed is sharp	8
2. Large shells of *Ostrea georgiana* in a matrix of hard white limestone with patches of greenish clay. A few incrusting Bryozoa were found; other fossils are present but not determinable. Similar material is reported to extend to a depth of 70 feet. Thickness seen	7
1. Concealed interval to level of the mill pond (altitude 300 (?) feet above sea level)	5
	70

Outcrops of chert beds are abundant throughout Burke County. They range in altitude from about 300 feet above sea level in the northern part of the county, where they are found near the hilltops, to 200 feet or less in the stream beds of the southern part. Nearly all the chert appears to lie at practically the same horizon (near the top of the Barnwell) and may be residual from one thin but persistent bed of limestone.

The thickest and most extensive exposures are in bluffs along Rocky Creek (altitude about 280 feet above sea level) near the Louisville road, 3.3 miles southwest of Waynesboro. The slope up to 20 feet above water level in Rocky Creek is covered with great blocks of soft and porous to dense and vitreous red flint containing numerous poorly preserved fossils (*Turritella*, *Periarchus*, etc.). The bed is at least 15 feet thick.

Other notable outcrops of chert were found at the following localities: Waynesboro-Millen road 1 mile south of Waynesboro, altitude 260 feet above sea level; Waynesboro-St. Clair road 10 miles west of Waynesboro, altitude 335 feet, ledge 5 feet thick; Waynesboro-Hephzibah road 3.1 miles northwest of Waynesboro, altitude 285 feet, 1 foot of vitreous chert overlying 5 feet of porous chert; Girard-Millhaven road 2.1 miles southeast of Girard, altitude 220 (?) feet; Girard-Millhaven road 7.3 miles southeast of Girard, altitude 220 (?) feet, fragments of white vitreous flint.

Chert beds exposed at Johnsons Landing and Stony Bluff on Savannah River in or opposite Screven County, along the lower course of Brier Creek below Girard, and at the former site of Millhaven on Beaverdam Creek were mapped as Vicksburg in the Coastal Plain report but without very strong paleontologic evidence. Vaughan[1] later suggested that the rock at Johnsons Landing may be of Jackson age and stated that it contains *Pecten perplanus*, which is now considered diagnostic of the Jackson.

Recent investigations indicate that the main chert beds at all the localities cited are probably at the same geologic horizon as those exposed throughout Burke and Jefferson counties—that is, near the top of the Barnwell formation—but chert of later age may be present at some of them. The upper surface of the Barnwell therefore dips below water level in Savannah River between Stony Bluff and the mouth of Brier Creek, in Screven County.

RICHMOND COUNTY.

The Barnwell formation caps the hills north of McBean Creek, where it overlies the McBean formation, but in the absence of characteristic beds it is almost impossible to distinguish one formation from the other. In the vicinity of Bath and in the western part of the county the Barnwell contains at its base beds of indurated fuller's earth which directly overlie the Cretaceous. A long, narrow area of Barnwell beds caps the ridge between Butler and Spirit creeks and extends northwestward into Columbia County, where it overlaps the Lower Cretaceous beds to the edge of the crystalline area. As fossils are very rare in all the formations of Richmond County, the mapping of the contacts must depend largely on lithology and topography.

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[1] U. S. Geol. Survey Prof. Paper 71, p. 739, 1912.

A good section of the lower beds of the Barnwell formation is exposed near a spring on the north slope of Mount Enon, an isolated remnant of the original plain, near the Dean's Bridge road, 14 miles southwest of Augusta and about 3 miles northeast of Bath.

Section on north slope of Mount Enon.

	Feet.
Eocene:	
Barnwell formation:	
8. Apparently all red sand to top of hill. Near the top are fragments of dense banded cherty sandstone	60
Twiggs clay member:	
7. Soft white fuller's earth: as the top of the bed is not exposed, the thickness may be greater than indicated	3
6. Argillaceous sandstone with abundant but poorly preserved fossils and rounded quartz pebbles an inch in maximum diameter	1
5. Coarse yellow sand	11
4. Light-drab claystone, with angular and conchoidal fracture on weathering. Has a high SiO_2-Al_2O_3 ratio and is a silicified fuller's earth, exactly like that at Hatcher's Mill and at Wrens, Jefferson County	11
3. Gray plastic clay	1
Unconformity.	
Lower Cretaceous:	
2. Indurated sandy kaolin, or flint clay.	10
1. Kaolinic sand, etc., not measured.	
	97

The altitude of the top of the hill is about 400 feet.

At Bath about 25 feet of indurated fuller's earth is exposed in the slope above the spring and bath house on the Walker property, and the bed is seen at several other places in the vicinity, but at Hepzibah, 6 miles farther east, the fuller's earth beds are absent. In the pit of the Albion Kaolin Co. the Cretaceous kaolin is overlain by 100 feet of red and yellow argillaceous sand without any conspicuous clay beds.

COLUMBIA COUNTY.

The only Eocene deposits of Columbia County are several lobes that extend into the southern part of the county near Grovetown, Forrest, and Harlem, but some of the exposures are very interesting and important. The McBean formation is absent, and probably it never extended so far north. The calcareous beds found in the Barnwell farther south and west are here lacking, and the formation consists of beds of fuller's earth, clay shale, or lignite, lying directly above the Lower Cretaceous and overlain by red sand. An unconformity between the clay member and the red sand was noted at several places and may be of general occurrence throughout the county, and there are indications of local unconformities within the red sand. As the beds are all of shallow-water origin, these unconformities may have been produced by very slight oscillations in the level of the land or by currents.

Phinizy Gully.—The relations of the Barnwell strata to the Lower Cretaceous are well shown in a gully in the abandoned Augusta-Wrightsboro public road, 1 mile northeast of Grovetown, on the Phinizy property. This locality is especially interesting because it furnished a large collection of Eocene plants, described by Berry,[1] and because the unconformity between the Cretaceous and the Eocene is so well exposed here.

Section of Phinizy Gully, 1 mile northeast of Grovetown.

	Feet.
Eocene:	
Barnwell formation:	
6. Yellow to red argillaceous sand, coarse and pebbly near base. Caps hill to east of gully, to an altitude of 540 feet	50+
5. Laminated plastic greenish clay	0–3
4. Conglomerate of varicolored kaolin pellets in red sand. Contains some fragments of lignitized wood	0–2
Unconformity (?).	
Twiggs clay member:	
3. Laminated shaly fuller's earth, containing leaf impressions. The bedding dips west at a smaller angle than the unconformity below. Pinches out toward the east	0–6
Lower Cretaceous:	
2. Silicified white sandy kaolin or flint clay; has been described as "argillaceous sandstone." The bedding dips 10° E.; the unconformity above dips 15° W. in the head of the gully	12
1. Soft plastic white kaolin, interbedded with white and yellow sand, with some kaolin conglomerate near the bottom of the exposure	12

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[1] Berry, E. W., U. S. Geol. Survey Prof. Paper 84, pp. 130-131, 1914.

Grovetown.—Fuller's earth exposed in the railroad cut at Grovetown station extends 4 feet above track level and is overlain unconformably by red sand. The large cut south of the station shows 20 feet of cross-bedded red and white sand, overlying the fuller's earth. The altitude of the station is 495 feet above sea level, and the highest exposure of fuller's earth is at 500 feet.

Fuller's earth was formerly mined on the Fiske property, about a quarter of a mile east of the station. When visited in 1916 the pit was filled with water, but according to the section given by Veatch and Stephenson[1] it penetrated 10 to 12 feet of fuller's earth, which lay immediately above white clay of Lower Cretaceous age. The earth was not a commercial success for bleaching, probably because it contains a considerable amount of pyrite, which readily becomes oxidized to iron sulphate and sulphurous acid after drying.

From this pit were obtained collections of fossil plants, which have been studied and described by Berry.[2]

A well at Usry Bros.' gin, near Grovetown station, penetrated 12 feet of fuller's earth that is very massive and thick bedded and is cut by several systems of widely spaced joints. It is dark gray when fresh and wet but becomes almost white on drying and weathering. It contains flakes of mica, small crystals of pyrite, and fragments of carbonized wood and stems.

Chapman lignite mine.—About 3 miles south of Grovetown a bed of lignite and lignitic clay occupies the horizon of the Twiggs clay. This material was formerly mined by W. C. Chapman for use as a fertilizer filler, but it was sufficiently carbonaceous to be used as fuel under the boiler at the grinding plant.

Section in lignite pit 3 miles south of Grovetown.

	Feet.
Barnwell formation:	
13. Gray or brownish incoherent sand, capping the hill	3-4
12. Coarse red argillaceous sand, with a bed of fine gravel at the base	10
Apparent unconformity.	
11. White, yellow, and red laminated plastic clay	1-4
10. Coarse angular yellow quartz sand; contains limonite fragments and in places fine gravel	15
9. Varicolored cross-bedded sand and fine gravel, with some layers of white plastic clay a few inches thick	35
8. White to buff or pink plastic clay, filling depressions in the surface of the lignite	0-1
Unconformity.	
Twiggs clay member:	
7. Black lignite	2-4
6. Gray plastic clay	1
5. Black lignite	1
4. Gray clay, extremely plastic	1
3. Black lignite, containing large fragments of carbonized wood	1
2. Light-brown plastic lignitic clay	1.5
1. Dark-brown clayey lignite	1.5
	75±

JEFFERSON COUNTY.

Nearly the whole of Jefferson County is underlain by the Barnwell formation, and its outcrop covers all of the county except a part near the northern boundary, where several streams have cut their valleys down into the Lower Cretaceous beds, and the area south of Louisville, where the hills are capped by beds of Miocene (Alum Bluff) age or younger.

The Twiggs clay member is thin but fairly persistent and appears in a line of exposures of fuller's earth across the northern part of the county. In general, the fuller's earth of this county contains less iron and is whiter than the deposits farther west. Some of it is soft and very light and porous, but farther east a larger proportion has become indurated into rather hard rock by the deposition of silica in the pores. Some of the silicified fuller's earth resembles the indurated Cretaceous kaolins found in the same area but may be distinguished from them on analysis by its much higher ratio of silica to alumina. Southward from the northern border of the Barnwell formation the earth grades into calcareous clay, marl, and oyster-shell beds, which have few of the characteristics of a true fuller's earth.

The upper part of the Barnwell formation is made up of a considerable but unmeasured thickness of red sand containing thin beds of plastic clay, locally indurated layers of fossiliferous or barren sandstone and thin beds of fossiliferous flint residual from original lenses of impure limestone.

Louisville.—One of the best sections of the upper part of the Barnwell formation is exposed in a gully on the east slope of Rocky Comfort Creek, about 300 yards above the wagon bridge three-quarters of a mile west of Louisville.

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[1] Op. cit., p. 269.

[2] Berry, E. W., op. cit., pp. 129-163.

Section three-quarters of a mile west of Louisville.

Barnwell formation:	Feet.
8. Massive brilliant-red argillaceous sand	10+
7. Fine white silica or tripoli, probably a decomposed chert bed	1–2
6. Indurated yellow sand	6
5. Bluish and yellow mottled clay, laminated but rather plastic, intermediate in properties between fuller's earth and common pipe clay	3
4. Coarse gray sand with a little clay, partly concealed	14½
3. Gray sand and yellow clay, locally indurated.	2
2. Concealed interval	15
1. Blue calcareous fossiliferous argillaceous sand, weathering yellow; from creek (215 feet above sea level)	5
	57½

As the red sand bed, No. 8, continues to the level of Louisville Court House (315 feet above sea level), the total thickness is 100 feet.

A bed of *Ostrea georgiana* shells in a matrix of calcareous clay resembling fuller's earth is exposed at low water in the south bank of Ogeechee River, 200 yards upstream from Cowart's Bridge, 2.6 miles south of Louisville. The bed is entirely similar to those at Danville, Twiggs County, and at Shell Bluff. Its altitude is a few feet below the base of the section on Rocky Comfort Creek.

At Warren's Mill, on Big Creek 3 miles east-northeast of Louisville, a bed of rock containing *Ostrea georgiana* was excavated for use in building a dam. There are no natural exposures of the oyster bed, but above water level in the creek (altitude 245 feet above sea level) is exposed 3 feet of blue calcareous fuller's earth, which dries and weathers white. This grades upward, by interbedding, into yellow argillaceous sand containing laminae of fuller's earth and fragments of oyster shells.

Old Town.—At Old Town Plantation, 8.4 miles by road southeast of Louisville, a bed of rotten fossiliferous chert in the red sand is exposed on the slopes up to 20 feet above the level of a small creek (altitude between 220 and 250 feet). Collections of fossils made by S. W. McCallie, Earle Sloan, and T. W. Vaughan were identified by Vaughan, who supplied the following list of fossils for the Coastal Plain report:[1]

Mortonia sp.
Caricella pyruloides Conrad.
Turritella carinata Lea.
Mesalia vetusta (Conrad).
Calyptraea aperta (Solander).
Glycymeris staminea (Conrad).
Glycymeris idonea (Conrad).
Glycymeris n. sp.
Crassatellites protextus var. lepidus Dall.
Crassatellites n. sp.
Venericardia alticostata Conrad.
Cytherea perovata Conrad.
Spisula praetenuis (Conrad).
Corbula densata Conrad.
Lunulites distans Lonsdale.

More recent collections furnished the species in the following list:

Station 7428. Old Town road, east side of Boiling Spring Creek. J. E. Brantly, collector, 1915.
Mortonella quinquefaria (Say)?
Plejona petrosa (Conrad)?
Turritella carinata Lea.
Mesalia vetusta (Conrad).
Glycymeris staminea (Conrad).
Venus? sp.
Cytherea perovata Conrad.
Crassatellites protextus (Conrad) var.
Protocardia sp.
Diplodonta aff. D. ungulina (Conrad), very close to species in basal Jackson at Sims, Miss.

Wrens.—Fuller's earth is exposed at a number of localities in the vicinity of Wrens and has been cut by many wells in and around the village. The earth is almost white, nonplastic, and noncalcareous and shows various degrees of induration. A section is exposed on the north slope of Brushy Creek, on the Louisville road 1 mile south of Wrens.

Section 1 mile south of Wrens.

Barnwell formation:	Feet.
4. Yellow sand with interlaminated clay, conformable with the underlying fuller's earth	20
Twiggs clay member:	
3. Slightly indurated fuller's earth, porous, laminated, greenish when wet but becoming pure white on drying. Contains laminae and beds of greenish sand as much as several feet thick	20
2. Light-greenish argillaceous sand, slightly indurated	5
1. Concealed interval from creek level	5
	50

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[1] Georgia Geol. Survey Bull. 26, p. 292, 1911.

The section extends from 360 to 410 feet above sea level, and 410 feet is also the altitude of Wrens station.

Indurated fuller's earth unconformably overlies the Cretaceous at an altitude of 325 feet above sea level at Hatcher's Mill, on Reedy Creek 5.2 miles north of Wrens; and at Patterson's Bridge, on Brier Creek 7.7 miles northeast of Wrens, is an exposure of sandy laminated fuller's earth, a part of which is indurated and resembles that at Hatcher's Mill.

GLASCOCK COUNTY.

The unconformity separating the Lower Cretaceous from the Barnwell formation is plainly shown on the Gibson-Mitchell road at Jumping Gully Creek, 2 miles west of Gibson. The section at this locality was given by Veatch and Stephenson[1] and need not be repeated here. All the strata above the Cretaceous-Eocene unconformity, which lies at an altitude of 410 feet, should be referred to the Barnwell formation.

An interesting section, which shows the variability of the basal beds of the Barnwell, is exposed in the pits of the Harbison & Walker Refractories Co., east of milepost 48 on the Augusta Southern Railroad, 2 miles east of Gibson. The pits are in the eastern escarpment of Rocky Comfort Creek.

Section in fire-clay mine 2 miles east of Gibson.

	Feet.
Eocene:	
Barnwell formation:	
4. Yellowish sand with few pebbles	7
3. Conglomerate of yellow sand and pebbles; where bed 2 is absent, this bed rests directly upon the Cretaceous	0–6
2. Gray to yellow indurated laminated clay or shale, with leaf impressions; at the base is a patch of impure lignite which grades upward into the gray plastic clay; fills erosion hollows in the surface of the Cretaceous	0–4
Unconformity (altitude 340 feet above sea level).	
Lower Cretaceous:	
1. Gray fire clay and indurated kaolin, not very hard but extremely brittle	10–15

On the Gibson-Warrenton road 1.4 miles north of Gibson is exposed a section of the entire Cretaceous and lower part of the Eocene. There are no fossil-bearing beds, but the section is typical of deposition near the shore line.

Section at Rocky Comfort Creek 1.4 miles north of Gibson.

	Feet.
Eocene:	
Barnwell formation:	
9. Massive red sand to top of hill	45
8. Interbedded red sand and red and gray plastic clay	10
7. Mottled argillaceous sand, without kaolin fragments	20
6. Mottled argillaceous sand, with small angular fragments of indurated kaolin	7
5. Fine gravel, with angular fragments of indurated kaolin	1
4. Limonite-cemented sandstone	.1
Unconformity.	
Lower Cretaceous:	
3. Yellow, white, and mottled kaolinic sand	5
2. Concealed interval	50
Pre-Cambrian (?):	
1. Granite	20
	158.1

The altitude of this section is 355 to 515 feet above sea level, and the Cretaceous beds occupy only the interval from 375 to 430 feet. The granite mass outcropping to 20 feet above the level of the creek is probably a hill or monadnock in the pre-Cretaceous surface, as no more igneous rock is seen for some miles farther north.

Other localities in Glascock County, with the fossils obtained at them, have been discussed on pages 46–47.

WASHINGTON COUNTY.

The Barnwell formation is present throughout a large part of Washington County. The bed within the formation most easily recognized by its lithology is the fuller's earth of the Twiggs clay member, which, although discontinuous and variable in thickness, can be traced by a line of outcrops from Oconee across the county to Chalker. The beds underlying the fuller's earth average about 50 feet in thickness and consist chiefly of calcareous clay and sand, with locally indurated beds of quartzite containing a characteristic lower Jackson fauna. Above the Twiggs clay member is red sand, with lenses of impure limestone containing *Mortonella quinquefaria* (Say), which probably represent the chert zones of Jefferson and Burke counties. The exposures of limestone extend from Wring Jaw Landing, on Oconee River a short distance south of the Washington County line, to Sunhill, passing between Sandersville and Tennille, and outliers of the same rock are thought to occur 2½ miles south of Warthen, but details are not available.

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[1] Op. cit., p. 273.

Buffalo Creek.—The Barnwell formation is well exposed in the steep escarpment east of Buffalo Creek, and sections have been measured along the roads east of Sheppard's Bridge, which is 3 miles north of the mouth of the creek and east of Turnpike Bridge, 5 miles farther north.

Section along road east of Sheppard's Bridge, 1½ miles north of Oconee.

	Feet.
Eocene:	
Barnwell formation:	
9. Red sand with plastic clay, laminated toward base	70
Twiggs clay member:	
8. Plastic laminated yellowish-green clay	12
7. Light-yellow nonplastic porous fuller's earth	5
6. Gray plastic clay, more or less sandy	14
5. Massive gray argillaceous sand, with casts of fossils, *Pecten perplanus*, *Panope*, *Glycymeris*	6½
4. Interbedded sand and fuller's earth	7½
3. Gray, very plastic sandy clay, becoming more sandy toward the top. The upper portion contains *Flabellum* and other poorly preserved fossils	27
2. Gray sand, mottled with red; at base contains quartz pebbles as much as 1½ inches long; clay laminae near the top	6
Lower Cretaceous:	
1. Cross-bedded kaolinic sand from level of Buffalo Creek. This may include the basal beds of the Eocene, as the contact has not been exactly determined	70
	218

The altitude of the base of bed 2 of the preceding section is about 285 feet above sea level.

Section along road east of Turnpike Bridge.

	Feet.
Eocene:	
Barnwell formation:	
9. Red sand	35
Twiggs clay member:	
8. Greenish plastic laminated sandy clay	10
7. Fuller's earth. The exposures are not quite continuous, and there may be interbedded sandy strata in the covered intervals. All the earth in sight, however, appears to be of sufficient purity for use as a bleaching earth. It is light greenish yellow, fine grained, nonplastic, noncalcareous, and somewhat iron stained on account of its proximity to the surface but contains very little sand	40
Eocene—Continued.	
Barnwell formation—Continued.	Feet.
Twiggs clay member—Continued.	
6. Covered interval. Beds probably of same character as the next underlying stratum. A spring emerges near the top of the interval	20
5. Dark-gray sandy clay	5
4. Greenish, slightly plastic clay, resembling fuller's earth in appearance, containing considerable sand and a few fossils	25
3. Sandy and calcareous clay, containing *Flabellum*	3
2. Gray sandy clay at base, grading upward into blue or greenish, very plastic gumbo or pipe clay	12
Unconformity (altitude 300 feet above sea level).	
Lower Cretaceous:	
1. Light-colored sand containing lenses of white kaolin, from level of Buffalo Creek	70
	220

Sandersville.—Near the Little Keg Creek bridge, 7.2 miles by road northwest of Sandersville and 8 miles in an air line northeast of Turnpike Bridge (see section and discussion, p. 48), the fuller's-earth bed is not present, but it comes in again farther south and is exposed where the same road crosses Rocky Branch, 3.2 miles by road northwest of Sandersville.

Section along public road south of Rocky Branch, 3.2 miles northwest of Sandersville.

	Feet.
Barnwell formation:	
6. Massive red sand to top of hill	90
5. Gray and yellow argillaceous sand	12
Twiggs clay member:	
4. Greenish fuller's earth, containing a few laminae of sand	10
3. Red sand with laminae and thin beds of greenish fuller's earth	10
2. Gray and greenish clay, becoming sandy and fossiliferous toward the top	7
1. Concealed interval from level of Rocky Branch	5
	134

As the base of this section is at an altitude of 330 feet, it can not be far above the top of the Cretaceous.

Limestone referred to the upper part of the Barnwell formation is exposed at the spring and lime sink at the head of Limestone Creek, 1 mile south of the courthouse at Sandersville. The topographic relations of the exposures are well shown in the sketch map by Brantly.[1] The section is as follows:

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[1] Brantly, J. E., Limestones and marls of the Coastal Plain of Georgia. Georgia Geol. Survey Bull. 21, p. 59, 1916.

Section 1 mile south of Sandersville.

	Feet.
Barnwell formation:	
6. Red sand to top of hill	10±
5. Coarse gray sandstone, irregularly indurated and terminating laterally in red sand	6
4. Gray sand, oxidized red and yellow, exposed along road	15
3. Light-gray chalky limestone; contains *Mortonella quinquefaria* (Say) in abundance and casts of other fossils; *Ostrea georgiana* is reported here.[1] Exposed in sink	12
2. Gray, very sandy limestone with obscure fossils	5±
1. Bright-blue incoherent sand, apparently grading laterally into gray sandy limestone. Exposed in stream below sink	2

The altitude of the base of the exposure is 400 feet, which must be approximately 100 feet above the top of the Cretaceous and stratigraphically higher than the calcareous fuller's earth and limestone beds found in a well near Limestone Church, 3 miles down the creek. The yellowish and mottled sands that cap the hills within a mile south of this exposure probably belong to the Alum Bluff formation, which overlaps the beds of Vicksburg age.

Sunhill.—Limestone of the same horizon as that exposed at Sandersville was formerly used in the manufacture of lime at Sunhill. The old kiln and quarry are on the south slope of Williamson's Swamp Creek, an eighth of a mile southeast of the station. Brantly [2] gives the following section:

Section in old quarry at Sunhill.

	Feet.
5. Red argillaceous sand	10
4. Medium-grained white sand grading into yellow sand	5
3. White calcareous clay	2
2. Arenaceous limestone or calcareous sandstone	3
1. Hard white compact, partly crystalline limestone	9
	29

As the altitude of the base of this section is 355 feet above sea level and as the normal dip of the beds is about 10 feet to the mile toward the southeast, the limestone must lie at about the same horizon as that at Sandersville.

Specimens of *Mortonella quinquefaria* (Say) in a matrix of limestone like that near Sandersville and Sunhill, collected by S. W. McCallie on the T. W. Smith farm, 2½ miles south of Warthen (U. S. G. S. station 3953), indicate the presence of outliers of this bed several miles north of the exposures described.

Warthen.—A good exposure of the Twiggs clay member of the Barnwell formation is found on the property of A. J. Irwin, 3 miles south of Warthen and 6 miles north of Sandersville, at the head of a branch of Little Keg Creek.

Section on Irwin property, 3 miles south of Warthen.

	Feet.
Barnwell formation:	
5. Massive red sand. This bed overlies the clay with a sharp contact, showing no sign of gradation, which may represent a local unconformity	40
Twiggs clay member:	
4. Greenish plastic clay and indurated sandy clay	2
3. Good fuller's earth, brownish gray when dry, laminated, brittle, and free from grit	8
2. Plastic greenish clay, with a tendency to crumble on drying	15
1. Greenish sandy, nonplastic clay resembling fuller's earth, containing thin beds of sand and plastic clay	20
	85

This section extends from 365 to 450 feet above sea level, with the top of the clay member at 410 feet. The normal dip of the beds would carry the clay well below the limestone exposures at Sandersville and Sunhill.

On the property of John and George Powell, about 1 mile north of the locality on the Irwin property just described, are outcrops of a bed of white to dark-brown cherty sandstone containing small masses and veinlets of iridescent opal, some of which are said to be large enough to cut as gems. Much fragmental material from this bed is scattered in the vicinity of the outcrops. The chert contains silicified fragments of echinoids, but determinable fossils are rare.

The stratigraphic position of this chert bed is very near the base of the Barnwell. Beds of chert and sandstone at the base of the Barnwell are more extensively developed and more fossiliferous farther northeast, in the vicinity of Chalker and Gibson.

Chalker.—Near milepost 65 on the Augusta Southern Railroad, 1¼ miles southwest of Chalker, a lens of sandy kaolin of Lower Cretaceous age (used in the manufacture of common pottery) is overlain unconformably by 6 feet of bedded yellow to white clayey sand of

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[1] Veatch, Otto, and Stephenson, L. W., Georgia Geol. Survey Bull. 26, p. 253, 1911.

[2] Op. cit., p. 61.

Eocene age. A quarter of a mile southwest of the pottery pit about 10 feet of indurated fuller's earth is exposed above the railroad level, overlain by a thin bed of quartzite, and below the railroad level and just above the Cretaceous is a bed of hard fossiliferous sandstone. The following species were obtained at this locality:

Station 7708. Base of Barnwell formation, Augusta Southern Railroad, 1½ miles southwest of Chalker, Washington County, Ga., Cooke and Shearer, collectors, 1916.

- Mesalia vetusta Conrad.
- Turritella carinata Lea.
- Cerithium sp.
- Glycymeris staminea (Conrad).
- Mytilus texanus (Gabb).
- Corbula alabamiensis Lea.
- Meretrix sp.
- Venericardia sp.

To these should be added *Flabellum cuneiforme* Lonsdale, *Barbatia cuculloides* (Conrad), and *Ostrea georgiana* Conrad? (identified by T. W. Vaughan[1]), which were collected by S. W. McCallie at the same locality (station 3945).

One mile south of Chalker, where the road to Sandersville ascends from the Ogeechee Valley to the upland plain, a section is exposed which carries no fossiliferous beds but shows well the character of the Barnwell formation.

Section along Sandersville road 1 mile south of Chalker.

	Feet.
Eocene:	
Barnwell formation:	
10. Massive red and mottled sand to top of hill	30
9. Red sand with laminae of white and bright-purple clay. This coloring is characteristic of the Alum Bluff formation in the southern part of the State, but it is unlikely that that formation extends so far north	17
8. Yellow and mottled sand	16
Twiggs clay member:	
7. Greenish laminated fuller's earth, stained and somewhat plastic on account of weathering	11
6. Coarse yellow sand	11
5. Greenish laminated fuller's earth, free from sand	1
4. Concealed interval	10
3. Fuller's earth containing a little sand	4
2. Sand with laminae of fuller's earth	4
Lower Cretaceous:	
1. White sand with kaolin lenses; to level of Chalker station	55
	159

The Cretaceous surface in this area, as well as in the counties farther east, is much more irregular than to the west, showing a drop of no less than 50 feet between this exposure (altitude about 385 feet) and the vicinity of the sandstone exposures not more than a mile away.

WILKINSON COUNTY.

The upland areas of Wilkinson County are underlain by beds of Jackson age, but Oconee River and Commissioners and Big Sandy creeks have cut their valleys down into the Lower Cretaceous strata. The Barnwell strata cover the southern part of the county and form a narrow lobe along the ridge between Big Sandy and Commissioners creeks and an elongated erosional outlier between Commissioners Creek and Oconee River. Both of the latter areas extend beyond the northern boundary of the county. Chert of Vicksburg age is found along the southern county line, and it is possible, as in Twiggs County, that a part of the red sand farther north belongs to that formation.

A gradual change in the character of the deposits of Jackson age from west to east is noticeable in the area between Ocmulgee and Oconee rivers. The Tivola tongue of the Ocala limestone is nearly 50 feet thick along the Ocmulgee, in Twiggs and Houston counties, but it pinches out before reaching the Oconee. In Wilkinson County it is thin and very impure and is absent at many localities. The largest exposure is on the property of the General Bauxite Corporation near Toomsboro, but the bed there carries only about 50 per cent of calcium carbonate, the remainder being sand and clay. The limestone that is exposed on Oconee River at Wring Jaw Landing, Johnson County,[2] is correlated not with the bryozoan-bearing limestone of the southwestern part of the State but with the limestone beds at a higher Jackson horizon which are exposed near Sandersville. (See pp. 68–69.)

In Wilkinson County the Twiggs clay member is less persistent and less pure than in Twiggs County, and the material is generally too sandy or calcareous to serve as a commercial fuller's earth. Locally both limestone and fuller's earth are absent, and the Barnwell formation consists entirely of red sand with a few thin beds of plastic clay or gumbo.

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[1] Georgia Geol. Survey Bull. 26, p. 276, 1911.

[2] Veatch, Otto, and Stephenson, L. W., op. cit., p. 305.

Gordon.—A section typical of the beds in the northern part of the county is exposed in a pit of the Savannah Kaolin Co., 1 mile south of Gordon.

Section in pit of Savannah Kaolin Co.

	Feet
Eocene:	
Barnwell formation (upper part):	
5. Red and mottled argillaceous sand to the top of the hill	60
Twiggs clay member:	
4. Greenish-yellow fuller's earth, containing chalk nodules and a few fossils	10
Ocala limestone (Tivola tongue):	
3. Sandy limestone, with *Pecten perplanus* and abundant bryozoa	4
Barnwell formation (basal part):	
2. Argillaceous glauconitic sand filling erosion depressions in the Cretaceous surface	0-2
Unconformity.	
Lower Cretaceous:	
1. Massive white kaolin	30
	106

Bed 3 of this section represents the tip of the Tivola tongue of the Ocala limestone.

Big Sandy Valley.—In the exposures along the Valley of Big Sandy Creek the Tivola tongue of limestone is generally absent or is represented by local beds of fossiliferous chert, but the fuller's earth bed is well developed. A typical section is exposed along the public road on the southwest side of Big Sandy Creek near Sand Bed Bridge, 3 miles south of Irwinton.

Section near Sand Bed Bridge, on southwest side of Big Sandy Creek.

	Feet.
Eocene:	
Barnwell formation:	
6. Red, yellow, and mottled argillaceous sand, containing some thin beds of plastic clay	40
Twiggs clay member:	
5. Thin bed of sticky yellowish clay, not well exposed	5?
4. Fuller's earth, containing a few partings of yellow sand not over 1 inch thick, but the greater part of the interval is thick-bedded light-colored earth	25
3. Very plastic bluish clay; several feet exposed, but the top and bottom of the bed are concealed	5?
2. At bottom red sand with laminae of clay resembling fuller's earth; above, mottled red and bluish clayey sand	25
Unconformity.	
Lower Cretaceous:	
1. Massive white kaolin	15
	115

Toomsboro.—In the immediate vicinity of Toomsboro no limestone nor fuller's earth is exposed and the Barnwell seems to consist entirely of red sand, but the missing beds crop out on the property of the General Bauxite Corporation, 3 miles west of the station. No complete section is exposed. The following section is made up from aneroid readings taken at widely separated outcrops:

Section on property of the General Bauxite Corporation, 3 miles west of Toomsboro.

	Altitude in feet.
Eocene:	
Barnwell formation:	
5. Red sands capping hills.	
Twiggs clay member:	
4. Calcareous fuller's earth	300
Ocala limestone (Tivola tongue):	
3. Hard and soft yellow impure limestone (50 per cent $CaCO_3$), containing *Pecten perplanus*, *Periarchus pileus-sinensis*, and Bryozoa of the Rich Hill facies of the Jackson fauna	270-290
Unconformity	250
Lower Cretaceous:	
2. Bauxite lenses.	
1. Kaolin and kaolinic sands.	

BALDWIN COUNTY.

So far as known, only one lobe of the Barnwell formation enters Baldwin County. The Barnwell material forms the overburden at the fire-clay pits of the Stevens Bros. Co., at Stevens Pottery; and in one of these pits the section given below was measured.

Section in clay pit, Stevens Pottery.

	Feet.
Eocene:	
Barnwell formation (Twiggs clay member):	
5. Soil, consisting of weathered fuller's earth mixed with red sand	3
4. Fuller's earth, sandy, iron-stained, of higher specific gravity than commercially valuable earth of Twiggs County but very similar to the latter in appearance and composition; contains casts of fossils	12
3. Blue argillaceous marl; Bryozoa very abundant in lower part; Mollusca more abundant toward top	10
2. Light-green glauconitic clayey sand filling minor irregularities in the Cretaceous surface; contains a few Bryozoa	0-2
Lower Cretaceous:	
1. Massive kaolin, locally sandy or bauxitic, used as fire clay	20
	47

Station 7755. Bed 3 of section at Stevens Pottery, Central of Georgia Railway, Baldwin County, Ga. C. Wythe Cooke, collector, 1916.

- Bryozoa (Rich Hill facies of Jackson fauna).
- Turritella cf. T. arenicola var. branneri Harris.
- Calyptraea sp.
- Nucula ovula Lea.
- Yoldia sp.
- Leda cf. L. coelata Conrad.
- Leda albirupina Harris?
- Panope oblongata (Conrad)?
- Pecten perplanus Morton?
- Pseudamusium sp.
- Corbula oniscus var. (probably) wailesiana Dall.
- Phacoides (Miltha) clairbornensis Conrad.
- Tellina sp.
- Tagelus? sp.
- Cytherea discoidalis Conrad? (also at Roberts).
- Venericardia planicosta (Lamarck).
- Venericardia sp.

JONES COUNTY.

Several small isolated areas of beds of Jackson age extend into the southern part of Jones County, locally overlapping the Lower Cretaceous deposits and resting upon the crystalline basement rocks.

Interesting exposures of fossiliferous beds occur in the cuts of the Georgia Railroad, near Roberts, 9.4 miles by rail northeast of Macon. The best section is shown in the cut 1 mile northeast of the station, near the overhead crossing of the Central of Georgia Railway.

Section in cut 1 mile northeast of Roberts.[1]

	Feet.
Eocene:	
Barnwell formation:	
6. Loose red sand, containing a few scattered quartz pebbles; no fossils observed	10
Twiggs clay member:	
5. Greenish and drab laminated sandy clay (fuller's earth), porous and of low, specific gravity	12
4. Laminated sandy clay containing white chalk nodules and casts of fossils. The upper 2 feet of the bed is very fossiliferous. This bed is a typical calcareous fuller's earth	8
3. Bluish fossiliferous mud or marl	8
Crystalline basement:	
2. Concealed a few feet	?
1. Crystalline igneous rock.	

The igneous rock does not appear in this cut but crops out in the next cut, a quarter of a mile farther northeast, where it is overlain by red sand. The highest altitude reached by the crystalline rock in this cut is 590 feet; the base of bed 3 in the section is 595 feet above sea level.

The amount of overlap of the Barnwell beds on the crystalline rock at this point is not great, for in a cut less than a mile south of Roberts the red sand of Jackson age unconformably overlies gray micaceous kaolinic sand of the Cretaceous.

Bed 3 closely resembles the corresponding stratum (No. 3) in the section at Stevens Pottery, and the sections are similar in other respects.

The exposures near Roberts were first studied by Harris,[2] who referred the strata to the upper Wilcox ("Lignitic"). Preliminary study of collections of fossils made by McCallie, Sloan, and Vaughan led Vaughan[3] to the conclusion that the beds are of lower Claiborne age. It appears, however, that the determinations of the most critical species were based on very imperfect material, and the correctness of some of them is open to question. The list of species as here revised contains a number of species in common with the lower Jackson fauna of Arkansas and bears a close resemblance to that of the species occurring in the lower part of the Barnwell formation near Gibson. This opinion of the age is in accordance with the lithologic and structural evidence, which shows that these beds are of the same age as the fuller's earth and bryozoan-bearing limestone of Twiggs County. The revised list of species follows:

Fossils from cut on Georgia Railroad 1 mile east of Roberts, Jones County.

[Identified by T. W. Vaughan; list revised by C. W. Cooke.]

	Collected by—	
	McCallie.	Sloan and Vaughan.
Endopachys maclurii (Lea)	....	×
Cylichna sp	×	....
Plejona petrosa (Conrad)	×	×
Clavelithes sp	×	....
Mazzalina sp	....	×
Levifusus branneri Harris?	....	×
Pseudoliva vetusta (Conrad)	....	×
Turritella apita De Greg	×	....
Turritella sp	....	×
Turritella carinata Lea?	×	....
Turritella arenicola Conrad	....	×
Natica sp	×	×
Calyptraea aperta (Solander)	×	....
Adeorbis sp	×	....
Nucula ovula Lea	×	×
Yoldia aff. Y. psammotaea Dall	×	....
Leda albirupina Harris	×	×
Leda sp	....	×
Trigonarca sp	×	×

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[1] Adapted from Veatch, Otto, and Stephenson, L. W., op. cit., p. 280.

[2] Harris, G. D., Eocene outcrops in central Georgia: Bull. Am. Paleontology, vol. 4, p. 4, 1902.

[3] Georgia Geol. Survey Bull. 26, p. 282, 1911.

Fossils from cut on Georgia Railroad 1 mile east of Roberts, Jones County—Continued.

	Collected by—	
	McCallie.	Sloan and Vaughan.
Glycymeris sp		×
Glycymeris trigonella (Conrad)?	×	×
Ostrea alabamiensis Lea		×
Pteria limula (Conrad)		×
Pecten n. sp		×
Pecten (Pseudamusium) scintillatus Conrad	×	
Modiolus alabamiensis Aldrich	×	
Periploma sp		×
Venericardia planicosta (Lamarck)	×	×
Protocardia, probably P. nicolleti (Conrad)		×
Phacoides (Miltha) claibornensis (Conrad)	×	×
Cytherea sp		×
Cytherea discoidalis Conrad?		×
Psammobia sp	×	
Spisula parilis (Conrad) or S. funerata (Conrad)		×
Corbula oniscus Conrad	×	×
Corbula alabamiensis Lea	×	×

TWIGGS COUNTY.

Vicinity of Pikes Peak.—The Twiggs clay member of the Barnwell attains its greatest thickness in Twiggs County, where, at Pikes Peak, it is mined for use as fuller's earth. The member changes considerably in character from north to south within the county. The best exposures in the northern part are on the property of the General Reduction Co., near Pikes Peak, where there are two well-defined beds of fuller's earth in an interval of about 100 feet. The lower bed is about 45 feet thick, the upper more than 20 feet, and the two are separated by a bed of greenish-yellow fossiliferous sand which reaches a thickness of 30 feet. The earth in this vicinity is not calcareous, except near the base, where it grades into limestone. Where leached and oxidized by surface water it has a pale-yellow to cream color and is extremely light and porous; but below the zone of oxidation it is usually dark gray and contains organic matter and pyrite. Farther south, in the neighborhood of Danville and Westlake, for instance, the fuller's-earth bed becomes thinner as the underlying limestone thickens and the clay becomes more and more calcareous. The calcareous clay is blue or gray when unoxidized, but becomes cream-colored or yellow at the surface. As it is much less pervious than the noncalcareous variety farther north, the zone of oxidation in many parts of its outcrop extends less than an inch from the surface, whereas in the northern part of the county the material is oxidized to depths of many feet.

Section in fuller's-earth mine of the General Reduction Co. half a mile northwest of Pikes Peak.

	Feet.
Barnwell formation (?):	
8. Massive dark-red sand	17
7. Fine quartz gravel, indistinctly bedded.	10
6. Varicolored sands with thin layers and fragments of sticky plastic "gumbo" clay. Some layers of the sand are slightly indurated	8
Unconformity (?).	
Twiggs clay member:	
5. Light-colored fuller's earth. The lower portion is thin bedded, with fine sandy partings stained by oxides of iron and manganese. Toward the top the earth becomes more massive, and the beds are several feet thick between partings. The whole mass of fuller's earth is cut by joints in various directions, and iron and manganese stains are found along the joint planes. Some of the joints and partings are slickensided, showing that slight movements, probably caused by shrinkage, have occurred. This bed, which is uniform in texture and composition and is very light and porous, constitutes the commercially valuable fuller's earth	17
4. Dark-colored fuller's earth, almost black when wet but becoming light gray on drying. The dark color is probably due to organic matter. The clay contains visible crystals of pyrite and gives off a strong odor of sulphur dioxide when dried at 100° C. It also contains scattered concretions of hard siliceous material. The black layer thins to the north and west—that is, the slope of its upper surface follows the slope of the hill. The line of contact with the light-colored earth is sharp and even, but there is no visible change in texture, and the contact was observed to cut obliquely across the sand partings (bedding planes). It is evident that the light earth has been derived from the dark variety by leaching and oxidation of pyrite and carbonaceous matter	5
3. Yellow-drab fuller's earth. The lower part of the bed is mottled and banded with grains and layers of dark-colored oxides of iron and manganese	1
2. Greenish-yellow sand containing some poorly preserved fossils. This bed is shown in borings in the floor of the mine and in wells near the mill	50
1. Light-yellow fuller's earth, penetrated in wells near the mill	?
	108

The irregularity of the upper surface of the fuller's-earth bed indicates an unconformity between beds 5 and 6, and an unconformity at the same horizon is seen between the red sand and the fuller's earth in the railroad cut at Pikes Peak station. In the absence of paleontologic evidence it can not be certainly stated whether this unconformity is within the Barnwell or whether it separates the Barnwell formation from the Vicksburg formation.

On the property of J. D. Crump, which adjoins that of the General Reduction Co. on the northwest, and on the Lowe Wall property, 1 mile farther south, 12 feet of limestone containing Bryozoa (Rich Hill facies of Jackson fauna), *Periarchus pileus-sinensis*, and *Pecten perplanus* occurs at an altitude a little more than 100 feet lower than the top of the fuller's earth in the section just given (which is 585 feet above sea level). The limestone is underlain by tenacious yellow sand.

Gallemore.—A fossiliferous marl, consisting of fine quartz sand in a matrix of clay and calcium carbonate, is exposed in the bed of Turkey Creek (altitude, 380 feet above sea level) at Gallemore, or Willis, 4 miles northeast of Danville. That this marl is a shoal-water deposit of Jackson age is shown by the species in the following list:

Station 7699. Boulders below mill at Gallemore, Twiggs County, Ga. C. Wythe Cooke, collector, 1916.
- Plejona petrosa (Conrad).
- Mesalia vetusta (Conrad).
- Nucula sp.
- Leda coelata (Conrad)?
- Glycymeris staminea (Conrad)?
- Corbula oniscus Conrad.
- Spisula parilis Conrad?
- Panope sp.
- Meretrix sp.
- Phacoides (Miltha) claibornensis (Conrad).
- Phacoides (Miltha) pandatus (Conrad)?
- Phacoides (Here) alveatus (Conrad).
- Venericardia planicosta (Lamarck).

All these species are represented by casts and molds. The following additional species, identified by T. W. Vaughan, were cited from this locality by Veatch and Stephenson:[1] *Calyptraea aperta* (Solander), *Turritella carinata* Lea, and *Diplodonta ungulina* (Conrad)?

Section along public road east from Gallemore.

	Feet.
Oligocene (?): Vicksburg formation (?):	
7. Red argillaceous sand	60
6. Basal conglomerate of red sand containing limestone and quartzite pebbles	1
Unconformity (?).	
Eocene: Barnwell formation:	
5. Red sand	10
4. Plastic "gumbo" clay	2
3. Red sand	10
2. Concealed interval from creek to railroad level	15
1. Marl exposures in creek bed (station 7699)	?
	98

The unconformity between beds 5 and 6 may be the same as that seen at Pikes Peak.

Turkey Creek.—Beside the tracks of the Macon, Dublin & Savannah Railroad just south of Turkey Creek, 1½ miles northwest of Danville, hackly yellow fuller's earth, somewhat calcareous and containing several thin ledges of hard argillaceous limestone near the top, rises 10 or 15 feet above the swamp level. At the top (altitude about 380 feet) is a stratum of sandy calcareous clay loaded with shells of *Ostrea georgiana* associated with impressions of other mollusks, including a large *Mytilus?*.

Sections near Dry Branch have been described on pages 42–44 and need not be repeated here.

BIBB COUNTY.

An area underlain by the Barnwell formation extends into the southern part of Bibb County near Dry Branch and includes the localities at Browns Mountain and Bond's store which have already been described (pp. 47–48).

About 1½ miles south of Bond's store, on the John Tharpe estate near the boundary between Twiggs and Bibb counties, the fuller's-earth beds become very prominent but the bryozoan-bearing limestone and sandstone are absent. The section is well exposed in gullies above and below the level of the Macon-Marion road.

Section on the John Tharpe estate, Macon-Marion road 10 miles southeast of Macon.

	Feet.
Eocene:	
Barnwell formation:	
4. Red sand, probably extending to top of hill, 75 feet in all. Thickness seen	55
Twiggs clay member:	
3. Gray hackly fuller's earth, more or less sandy throughout but especially so at top and bottom. *Crassatellites* and fossil plants (station 7694) found 20 feet below top	80
2. Yellow sand to level of road	20
Unconformity.	
Lower Cretaceous:	
1. White plastic kaolin and kaolinic sand	?
	155

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[1] Op. cit., p. 256.

Prof. E. W. Berry has kindly furnished the following annotated list of plants collected by the writers at this locality:

Station 7694. Tharpe estate, 10 miles southeast of Macon.
  Acrostichum georgianum Berry (common; new to locality).
  Dodonaea viscosoides Berry (common).
  Ficus clairbornensis Berry (common).
  Pteris inquirenda Berry (new to locality; also at Newton, Miss.).
  Pisonia claibornensis Berry.
  Rhizophora eocenica Berry.
  Myrica nigricans Lesquereux (new to locality; also Green River formation of Wyoming. Referred by me to *Cupanites*).
  Potamogeton sp. (new).
  Carpolithus najasoides Berry, n. sp. (seed).

The following additional species were collected by Prof. Berry at the same locality:[1]

  Arundo pseudogoepperti Berry.
  Conocarpus eocenica Berry?
  Malapoenna sp.
  Mimosites georgiana Berry.
  Sphaerites claibornensis Berry.

South and west of Macon there are several isolated exposures of red sand with thin beds of plastic clay unconformably overlying the light-colored sands and clays of the Upper and Lower Cretaceous and resembling the Barnwell deposits of northern Houston County.

BLECKLEY COUNTY.

As the outcrops of the Barnwell beds in Bibb County are typical of near-shore deposition, those of the northern part of Bleckley County are typical of the deeper-water deposits now found near the southern limit of exposure of deposits of Jackson age. The deposits of Jackson age in this county are almost entirely calcareous, consisting of blue clay of the fuller's-earth type, sandy marl, and bryozoan-bearing limestone, overlain by red sand which belongs largely to the Vicksburg formation.

Ainslie.—An excellent exposure of the Tivola tongue of the Ocala limestone occurs on the east side of Shellstone Creek 1¼ miles east of Ainslie. The following section is adapted from that given by Brantly:[2]

Section on Weatherly place, on east side of Shellstone Creek, 1¼ miles east of Ainslie.

	Feet.
Residual Oligocene or Eocene:	
Vicksburg or Barnwell formation:	
6. Red argillaceous sand to top of escarpment. No sharp line of contact between this and the underlying bed	40
Eocene:	
Barnwell formation (Twiggs clay member):	
5. Cream-colored fuller's earth (weathered), with some sand	20
Ocala limestone (Tivola tongue):	
4. Hard pinkish, partly crystalline limestone.	1
3. Medium hard white, highly fossiliferous limestone	5
2. Soft white porous, friable, highly fossiliferous limestone	15
1. Creek bottom land	3
	84

The following fossils from the Weatherly place were identified by C. W. Cooke:

Upper 1 foot of bed 3:
  Periarchus sp.
  Semele? sp.
Lower 1 foot of bed 3:
  Lunulites sp.
  Flabellum wailesii Conrad?
  Endopachys maclurii (Lea)?
  Dentalium sp.
  Leda multilineata Conrad.
  Panope sp.
  Crassatellites sp.
Bed 2:
  Bryozoa (Rich Hill facies of Jackson fauna).
  Periarchus pileus-sinensis (Ravenel)?
  Pecten perplanus Morton.

Deese property.—Limestone and calcareous fuller's-earth beds of Jackson age are well exposed on the property of J. T. Deese on the southeast side of Shellstone Creek, 10 miles north of Cochran. The beds show local variations, but the following section, measured in a gully near the Deese residence, may be taken as typical.

Section on Deese property, near Shellstone Creek.

	Feet.
Oligocene or Eocene:	
Vicksburg or Barnwell formation:	
9. Red sand with chert ledges, to the flat summit of the hill	50
Eocene:	
Barnwell formation (Twiggs clay member):	
8. Blue calcareous fuller's earth, thin bedded, fossiliferous, more sandy than the underlying beds	3

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[1] Berry, E. W., The Upper Cretaceous and Eocene floras of South Carolina and Georgia: U. S. Geol. Survey Prof. Paper 84, p. 131, 1914.

[2] Brantly, J. E., Georgia Geol. Survey Bull. 21, p. 21, 1916.

	Feet.
Eocene—Continued.	
Barnwell formation—Continued.	
7. Thin bed of hard impure fossiliferous limestone, probably	2
6. Blue calcareous fuller's earth weathered to light yellowish gray at the surface	20
5. Blue calcareous fuller's earth, containing harder and more calcareous layers	10
4. Blue calcareous fuller's earth, almost free from sand and grit	20
3. Concealed interval	10
2. Interbedded hard massive blue argillaceous limestone and blue calcareous fuller's earth. (These are varying phases of the same formation, the hardness depending on the percentage of calcium carbonate)	5
1. Rotten fossiliferous limestone	5
	125

The base of this section (altitude, about 300 feet above sea level) is about 10 feet higher than the top of the Tivola tongue of the Ocala limestone exposed in the escarpment of Shellstone Creek 1½ miles northwest of the Deese residence and is stratigraphically above it.

HOUSTON COUNTY.

The deposits of Jackson age present considerable diversity in Houston County. The Tivola tongue of the Ocala limestone enters the county from the south, with a thickness estimated by Brantly[1] at 45 feet. Its outcrop forms a narrow belt across the south-central part of the county to Grovania, and the principal exposures are in the steep escarpments along the south side of Indian Creek and its tributaries. From Grovania the limestone outcrop swings northward along the Georgia Southern & Florida Railway to Bonaire and occupies an area more than 10 miles wide between the railway and Ocmulgee River.

The Tivola tongue appears to be absent north of Perry, but it has probably been removed from that area by erosion, for outliers of the bed occur farther north at Rich Hill, Crawford County.

The Tivola tongue of the Ocala limestone is overlain by the Twiggs clay member of the Barnwell formation, which in this county consists principally of calcareous cream-colored clay resembling fuller's earth, forms the upper slopes of the Indian Creek escarpment and of other hills, and attains a thickness of about 100 feet.

North of Perry red sand extends above the Cretaceous-Eocene unconformity to a maximum thickness of 50 feet. This bed probably corresponds in stratigraphic position with the yellow unconsolidated sands underlying the Tivola tongue of the Ocala limestone but may belong to the Midway formation.

Sections at Ross Hill and Mossy Hill, near Perry, are discussed on pages 44–46.

In the quarry of the Planters Limestone Co., near the crossing of the Georgia Southern & Florida Railway and the Perry-Fitzgerald branch of the Dixie Highway, 2 miles south of Tivola station, the following section is exposed:

Section in Planters Limestone Co.'s quarry, 2 miles south of Tivola.

	Feet.
Eocene:	
Barnwell formation (Twiggs clay member):	
2. Calcareous cream-colored clay resembling fuller's earth, grading downward into argillaceous marl. This material starts at the top of the hill southeast of the quarry and is exposed in bare washes on the slope. There are conspicuous harder and more calcareous ledges 20 and 22 feet above the base of the member. The marl at the base contains numerous Bryozoa, with *Ostrea trigonalis* and *Pecten perplanus*, but the upper fuller's-earth beds are not fossiliferous	33
Ocala limestone (Tivola tongue):	
1. Soft to medium-hard light cream-colored to white porous bryozoan limestone, exposed from the lowest point in the quarry to the top of the working face	39
	72

In a gully along the railroad siding near the quarry and probably not more than 5 feet below the bottom of the pit, there is an exposure of 7 feet of medium-grained yellow sand. The top of the Cretaceous can not lie far below.

The following fossils were obtained from bed 1 of the section:

Station 7689. Quarry 2 miles south of Tivola. Cooke and Shearer, collectors.

- Orthophragmina, stellately marked species.
- Lepidocyclina sp.
- Bryozoa (Rich Hill fauna).
- Periarchus pileus-sinensis (Ravenel).
- Cypraea fenestralis Conrad?
- Mesalia? sp.
- Ostrea sp.
- Pecten perplanus Morton.
- Panope sp.
- Protocardia nicolleti (Conrad)?

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[1] Brantly, J. E., op. cit., p. 82.

CRAWFORD COUNTY.

The interesting occurrence of strata of Jackson age at Rich Hill, 6 miles east of Roberta, has been well described by Veatch and Stephenson.[1] The variability of the strata, indicating deposition near the shore, is illustrated by the following additional sections described by Shearer:

Section in a gully on the north side of Rich Hill.

	Feet.
Eocene:	
Barnwell formation:	
4. Dark-red argillaceous sand, with thin beds of plastic clay near the base	30
Twiggs clay member:	
3. Fuller's-earth horizon. At the base the clay is greenish, coarse grained, and fossiliferous; at the top, massive, rather plastic, and stained by iron deposited from percolating water	25
2. Unconsolidated yellow sand, grading upward into fossiliferous yellow sandy clay, which here represents the Tivola tongue of the Ocala limestone	10
Unconformity.	
Lower Cretaceous:	
1. Kaolinic sand with a lens of massive kaolin at the top	100+
	165

Section in a gully on the south side of Rich Hill.

	Feet.
Eocene:	
Barnwell formation (upper part):	
8. Dark-red argillaceous sand, with thin beds of plastic clay near the base	40
Twiggs clay member:	
7. Fuller's-earth horizon. The clay is light greenish yellow in color, very slightly calcareous at the top but becoming more so toward the base	10
Ocala limestone (Tivola tongue):	
6. Hard massive argillaceous limestone	3
5. Soft massive argillaceous limestone, with few if any fossils	7
4. Bryozoan limestone of varying hardness. This is the bed from which the fossils listed below were collected	10
3. Sandy marl (gradational phase)	½
Barnwell formation (basal part):	
2. Unconsolidated light-yellow sand	25
Unconformity.	
Lower Cretaceous:	
1. Kaolinic sand with lenses of massive kaolin	100+
	195+

The fossils from Rich Hill, listed by T. W. Vaughan in the Coastal Plain report,[2] are as follows:

Periarchus pileus-sinensis (Ravenel).
Plejona sp.
Calyptraea aperta (Solander).
Ostrea georgiana Conrad.
Pecten perplanus Morton.
Pecten (probably P. nuperus Conrad), young and poor specimen.
Venericardia sp.
Lucina sp., found also 5½ miles south of Perry.
Panope sp.

The calcareous beds of the preceding sections are of undoubted Jackson age, and the Bryozoa of the Rich Hill facies of the Jackson fauna, as identified by R. S. Bassler, form valuable horizon markers.

The unconformity on the south side of the hill is 25 feet lower than that on the north side, showing an erosion depression in the Cretaceous surface, and in this depression the sand and limestone beds representing the Ocala are much thicker than over the old hilltops. The base of the deposits of Jackson age here is considerably higher than at any point in Houston or Twiggs counties, but the exact altitude is not known. The altitude of the top of the hill is probably about 700 feet.

OCALA LIMESTONE.

AREA NORTH OF DOOLY COUNTY.

The local details of the Ocala limestone in the area north of Dooly County have been given in the preceding discussion of the Barnwell formation and will not be repeated here. The type locality of the Tivola tongue of the Ocala limestone is described on page 76.

DOOLY COUNTY.

The Twiggs clay member of the Barnwell formation extends southward from Houston County into Dooly County but becomes increasingly calcareous and merges into the Ocala limestone. The Tivola tongue of the Ocala limestone is well developed in Dooly County and has been seen at a number of natural exposures.

On the J. M. Carter property, 1½ miles southeast of Lilly, 20 feet or more of soft white limestone composed largely of Bryozoa but containing also *Pecten perplanus* and *Periarchus*

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[1] Op. cit., pp. 299–300.

[2] Georgia Geol. Survey Bull. 26, p. 300, 1911.

pileus-sinensis is exposed. Brantly[1] reports 20 feet of limestone overlain by 17 feet of calcareous fuller's earth on the L. Frieden property, 9 miles east of Montezuma.

EXPOSURES ON AND NEAR FLINT RIVER.

Strata of Jackson age first appear in the banks of Flint River about 3½ miles above the crossing of the Seaboard Air Line Railway west of Cordele. From this point exposures occur at short intervals to Fort Scott, about 11 miles above the confluence of Flint and Chattahoochee rivers. As most of the exposures show little diversity, detailed discussion here will be restricted to those which have furnished the best collections of fossils or which are otherwise of interest.

The lithologic variation in the Ocala limestone, as displayed along Flint River, is slight. In the upper reaches of the river the rock, which presumably constitutes the lower portion of the formation, is prevailingly finer grained and less harsh in texture than that farther south, where tests of Foraminifera and Bryozoa compose a large proportion of the limestone.

Above Albany.—The following fossils were obtained from the Ocala limestone on Flint River 3 miles above the Seaboard Air Line Railway bridge:

Station 7106. Flint River at mouth of Spring Creek, Sumter County. Brantly and Cooke, collectors, 1914.
Orbitoid Foraminifera.
Flabellum wailesi (Conrad)?
Schizaster floridanus Clark?
Turritella sp.
Nucula sp.
Pecten perplanus Morton.
Crustacean.

The Ocala limestone exposed at this locality consists of about 14 feet of white or cream-colored limestone in thin beds, alternating in degree of hardness and containing a little glauconite. Analysis of the rock shows 85.8 per cent calcium carbonate.[2]

A quarter of a mile below this point the following fossils were obtained:

Station 7107. West bank of Flint River a quarter of a mile below the mouth of Spring Creek. Brantly and Cooke, collectors.
Orbitoid Foraminifera.
Bryozoa.
Periarchus, probably P. pileus-sinensis (Ravenel).
Mitra? sp.
Pecten perplanus Morton.
Amusium ocalanum (Dall).

The last two species named were found also at the railroad bridge below Spring Creek (station 7108).

At a small quarry on the Averitt property, 300 or 400 yards southwest of the corner of lots 7 and 26, half a mile east of Hugunen Ferry and 1 mile south of Daphne station, Crisp County (station 7237), the rock is a soft white limestone containing *Orthophragmina flintensis* Cushman, numerous Bryozoa, and an undetermined pecten, probably *Amusium ocalanum* (Dall). An analysis of the limestone from this locality given by Brantly[3] shows 85 per cent calcium carbonate. Better exposures of this rock occur in a sink about 300 yards east of the quarry, where 23 feet of soft argillaceous white limestone containing small specks of glauconite is overlain by 18 feet of reddish sandy loam. The course of an underground stream that flows through this sink can be traced northwestward by means of long, narrow slot-shaped sinks which expose it at intervals to Gum Creek.

The following section, which was measured by J. E. Brantly and C. Wythe Cooke on the east bank of Flint River 1 mile above the mouth of Cedar Creek, Crisp County, is quoted with a few minor changes from Brantly's report on the limestones and marls of Georgia.[4]

Section of Limestone Bluff on Armstrong place.

	Ft.	in.
Pleistocene:		
11. Sands and gravel	7	0
Ocala limestone:		
10. Mostly concealed, but with several small exposures of soft white, finely granular limestone and hard, partly crystalline light-gray limestone. Bryozoa, *Pecten*, etc	8	0
9. Hard, very light gray crystalline limestone		3
8. Alternating 6 to 10 inch layers of soft and slightly harder white, finely granular limestone	1	6
7. Hard, very light gray crystalline limestone		3
6. Alternating 6 to 10 inch layers of soft and slightly harder white, finely granular limestone	7	6
5. Medium-hard white, partly crystalline limestone	4	0
4. Soft white limestone	4	0
3. Hard white limestone containing Bryozoa; forms a projecting ledge	4	0
2. Soft light-gray limestone, with specks of glauconite and a few nodules of chert	8	0

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[1] Brantly, J. E., op. cit., p. 112.
[2] Idem, p. 120.
[3] Idem, p. 158.
[4] Idem, p. 159.

Ocala limestone—Continued.		
1. Hard white, partly crystalline limestone, irregularly weathered, to water's edge at 2-foot stage. Contains (station 7110) *Lunularia distans* and other Bryozoa, *Flabellum*, *Nucula*, *Glycymeris*, *Pecten*, *Amusium ocalanum*, and *Crassatellites*	2	6

On the east bank of Flint River at the bend to the west 6 miles below Burke Ferry and about 6 miles above the bridge of the Georgia Southwestern & Gulf Railway, near Warwick, Worth County (station 7115), the material exposed consists of white compact limestone rising 5 feet above water level and overlain by flint boulders, sand, and gravel. *Orthophragmina flintensis* Cushman and *Operculina* sp. were collected here.

The section at a bluff on the west bank of Flint River about 1¾ miles above the bridge of the Georgia Southwestern & Gulf Railway is as follows:

Section in bluff on west bank of Flint River.

	Feet.
3. Covered slope to top of hill	22
Ocala limestone:	
2. Hard ledges of compact white semicrystalline limestone (station 7117)	3
1. Compact white limestone, mostly soft but with harder places. Contains (station 7116) *Orthophragmina flintensis* and *Laganum*? *crustuloides* (Morton)? To water level at 4-foot stage	20

From bed 2 (station 7117) were collected the following:

Foraminifera:
  Orthophragmina flintensis Cushman.
Bryozoa:
  Several species.
Echinodermata:
  Laganum? crustuloides (Morton)?
Mollusca:
  Ostrea sp.
  Pecten perplanus Morton.
  Pecten suwaneënsis Dall.

On the east bank of Flint River in Worth County near the Dougherty County line, about 16 miles above Albany (station 7119), the rock consists of 5 feet of limestone, the upper part white, lower part gray, overlain by flint fragments. It contains *Orthophragmina flintensis* Cushman, *Operculina* sp., and *Pecten suwaneënsis* Dall. On the east bank of Flint River in Dougherty County, about 8 miles above Albany, at the mouth of a small creek (station 7235), the following fossils were obtained from soft white limestone, 8 feet in exposed thickness, containing concretionary masses of hard limestone:

Bryozoa.
Laganum? crustuloides (Morton).
Schizaster floridanus Clark?
Macropneustes mortoni (Conrad)?
Ostrea sp.
Pecten perplanus Morton.
Pecten suwaneënsis Dall.

Vicinity of Albany.—The following section was observed in the bank of Kinchafoonee Creek at the power plant 2 miles north of Albany:

Section on Kinchafoonee Creek 2 miles north of Albany.

	Feet.
4. River sands	15
Ocala limestone:	
3. Hard pink or yellow limestone with *Cidaris georgiana* and *Amusium ocalanum*	2½
2. Hard pinkish limestone with Bryozoa, echinoids, and *Amusium ocalanum*	2½
1. White, cream-colored, or yellow granular limestone with *Amusium ocalanum* and casts of corals. To water level in Kinchafoonee Creek	5

Above bed 3 there is reported to be 5 feet of limestone which was inaccessible at the time this section was measured. Other sections at this locality that do not differ materially from this have been recorded by Veatch and Stephenson[1] and by Brantly.[2]

The fossils in the following list were collected from loose blocks on the dump heap below the dam at the power plant:

Station 7121. Excavation below dam at power plant on Kinchafoonee Creek 2 miles north of Albany, Ga. Cooke and Brantly, collectors, 1914.
  Foraminifera:
    Operculina sp.
  Echinodermata:
    Cidaris georgiana Twitchell.
    Cassidulus (Rhynchopygus) depressus Twitchell?
    Cassidulus (Pygorhynchus) conradi (Conrad).
    Eupatagus carolinensis Clark?
    Linthia wilmingtonensis Clark?
    Macropneustes mortoni (Conrad).
  Mollusca:
    Eucymba ocalana Dall.
    Cypraea fenestralis Conrad.
    Ostrea sp.
    Gryphaeostrea sp.
    Pecten perplanus Morton, varieties.
    Amusium ocalanum Dall.
    Mya? sp.

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[1] Veatch, Otto, and Stephenson, L. W., op. cit., p. 316.

[2] Brantly, J. E., op. cit., p. 135.

Between Albany and Red Bluff.—The following fossils were found in white, gray, or cream-colored limestone extending about 2 feet above water level.

Station 7125. West bank of Flint River in Baker County about 3 miles below Dewberry Ferry (Baconton Landing) and about 13 miles above Newton. Brantly and Cooke, collectors, 1914.

- Flabellum sp.
- Cypraea fenestralis Conrad.
- Cerithium sp.
- Turritella sp.
- Calyptraea sp.
- Glycymeris sp.
- Pecten perplanus Morton.
- Pecten indecisus Dall.
- Amusium ocalanum (Dall)?
- Spondylus sp.
- Plicatula, Ocala sp.
- Venericardia sp.

The following species were collected from lumps of hard limestone excavated from the channel:

Station 7126. East bank of Flint River at Dry Bread Shoals, Mitchell County, 8½ or 9 miles below Newton.

- Foraminifera:
  - Orthophragmina mariannensis var. papillata Cushman.
  - Orthophragmina georgiana Cushman.
- Anthozoa:
  - Trochoseris n. sp.
- Echinodermata:
  - Cidaris georgiana Twitchell.
  - Laganum? crustuloides (Morton)?
  - Oligopygus haldermani (Conrad).
- Mollusca:
  - Mitra sp.
  - Chama sp.
  - Limopsis sp.
  - Barbatia sp.
  - Ostrea trigonalis Conrad.
  - Amusium ocalanum (Dall).
  - Pecten perplanus Morton.
  - Spondylus sp.
  - Plicatula, Ocala sp.
  - Mya? sp.
  - Venericardia vicksburgiana Dall.
  - Venericardia sp.
  - Crassatellites sp.

Station 7127. Loose blocks excavated from the channel of Flint River, a quarter of a mile below Norman's Ferry, Mitchell County, midway between Newton and Bainbridge. Cooke and Brantly, collectors, 1914.

- Lepidocyclina sp. and other Foraminifera.
- Lunularia sp. and other Bryozoa.
- Cidaris georgiana Twitchell.
- Oligopygus haldermani (Conrad).
- Laganum sp.
- Cypraea sp.

Station 7127—Continued.

- Xenophora sp.
- Glycymeris sp.
- Barbatia sp.
- Amusium ocalanum (Dall) var.
- Spondylus sp.
- Lima halensis Dall.
- Plicatula, Ocala sp.
- Chama sp.
- Crassatellites sp.
- Venericardia sp.
- Mya? sp.

On the east bank of Flint River in Decatur County, 1 mile below Windell's Landing and about 15 miles above Bainbridge (station 7129), *Orthophragmina mariannensis* var. *papillata* Cushman and an undetermined species of *Pecten* were found in 5 feet of irregularly weathered pinkish limestone.

Vicinity of Bainbridge.—The Ocala limestone is the oldest formation in the vicinity of Bainbridge, and all its exposures appear to represent a single horizon. It is a soft, coarsely granular limestone varying in color from white to yellow and composed largely of tests of Foraminifera and Bryozoa, which on exposed surfaces have become firmly cemented or "case-hardened" into a brittle, semicrystalline limestone, but which when freshly exposed are only slightly coherent. The rock appears to lie very nearly horizontal, but the upper surface is exceedingly irregular and jagged, with pinnacles extending in places to 20 feet above water level. The irregularity is due in part to erosion prior to the deposition of the overlying materials and in part to subsequent solution. The Ocala is overlain unconformably by a complex series of red and variegated sands and carbonaceous clays containing chert fragments with impressions and siliceous pseudomorphs of mollusks and corals of lower Oligocene age. The Ocala itself appears to have been subjected to the silicifying agencies to a lesser extent, for chert fragments carrying Ocala fossils are only occasionally found. The accidental inclusion of some of these in the collections of the coralliferous chert has unfortunately been interpreted as a mingling of the Ocala and Chattahoochee faunas.[1]

The following species have been identified from localities near Bainbridge:

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[1] Dall, W. H., A contribution to the invertebrate fauna of the Oligocene beds of Flint River, Ga.: U. S. Nat. Mus. Proc., vol. 51, p. 488, 1916.

Station 7099. East bank of Flint River half a mile above Red Bluff. C. Wythe Cooke, collector.

- Foraminifera:
  - Orthophragmina georgiana Cushman.
- Bryozoa:
  - Many species.
- Echinodermata:
  - Oligopygus haldermani (Conrad).
  - Agassizia conradi (Bouvé)?

Stations 3387, 6159, 7098. Red Bluff, Flint River, 7 miles above Bainbridge. Vaughan, Stephenson, and Cooke. collectors.

- Foraminifera:
  - Orthophragmina americana Cushman.
  - Orthophragmina mariannensis Cushman.
  - Orthophragmina georgiana Cushman.
  - Orthophragmina vaughani Cushman.
- Bryozoa:
  - Many species.
- Echinodermata:
  - Oligopygus haldermani (Conrad).
  - Laganum? crustuloides (Morton)?
  - Cassidulus (Pygorhynchus) georgiensis Twitchell.
  - Agassizia conradi (Bouvé).
- Mollusca:
  - Pecten perplanus Morton.
  - Pecten indecisus Dall.
  - Pecten suwaneënsis Dall.
  - Amusium ocalanum (Dall).

Station 7097. Bluff on east side of Flint River near old factory three-quarters of a mile north of the Atlantic Coast Line Railway station at Bainbridge. Vaughan, Cooke, and Mansfield, collectors.

- Foraminifera:
  - Orthophragmina georgiana Cushman.
  - Lepidocyclina sp. and many others.

Station 7097—Continued.

- Bryozoa:
  - About 34 species, most of them new.
- Echinodermata:
  - Cidaris georgiana Twitchell.
  - Cassidulus (Pygorhynchus) conradi (Conrad).
  - Oligopygus haldermani (Conrad).
  - Agassizia conradi (Bouvé).
  - Eupatagus carolinensis Clark?
- Mollusca:
  - Ostrea, 2 sp.
  - Pecten perplanus Morton.
  - Amusium ocalanum (Dall).
  - Plicatula, Ocala sp.
  - Cardium sp.

Stations 3293, 6171. Bainbridge. A. H. Brooks and L. W. Stephenson, collectors.

- Lepidocyclina sp. and other Foraminifera.
- Bryozoa, many species.
- Cidaris georgiana Twitchell.
- Cassidulus (Pygorhynchus) georgiensis Twitchell.
- Oligopygus haldermani (Conrad).
- Ostrea trigonalis Conrad.
- Pecten perplanus Morton.
- Amusium ocalanum (Dall).

EXPOSURES WEST OF FLINT RIVER.

For local details of the Ocala limestone west of Flint River, the reader is referred to the county descriptions in Brantly's report on the limestones and marls of the Coastal Plain of Georgia.[1]

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[1] Brantly, J. E., Georgia Geol. Survey Bull. 21, 1916.

THE STRUCTURE AND STRATIGRAPHY OF GRAVINA AND REVILLAGIGEDO ISLANDS, ALASKA.

By Theodore Chapin.

INTRODUCTION.

SCOPE OF PAPER.

This paper is intended to supplement a report by Philip S. Smith[1] on the same region. The finding on Gravina Island of Triassic fossils, which previously had been reported from but one other locality in southeastern Alaska, made his paper of particular interest. Since the publication of Smith's report the writer has had the opportunity to make further studies and to gather additional data on the structure and stratigraphy of the rocks of Gravina Island and adjacent regions. The discovery of fossils of Jurassic or Cretaceous age has made possible some changes in the geologic mapping and furnished the basis for the interpretations which are here presented, not as final conclusions but as a reasonable working hypothesis for future field work. The structure and stratigraphy of the rocks of Gravina Island are more clearly understood by a consideration of their relation to a larger area including a part of Revillagigedo Island (fig. 10).

This paper is a preliminary report on an area in the southern part of the Ketchikan district. A more complete report on the whole district, including a description of the mineral resources, is now in preparation. The accompanying geologic sketch map (fig. 11) is drawn from the field notes of P. S. Smith and the writer.

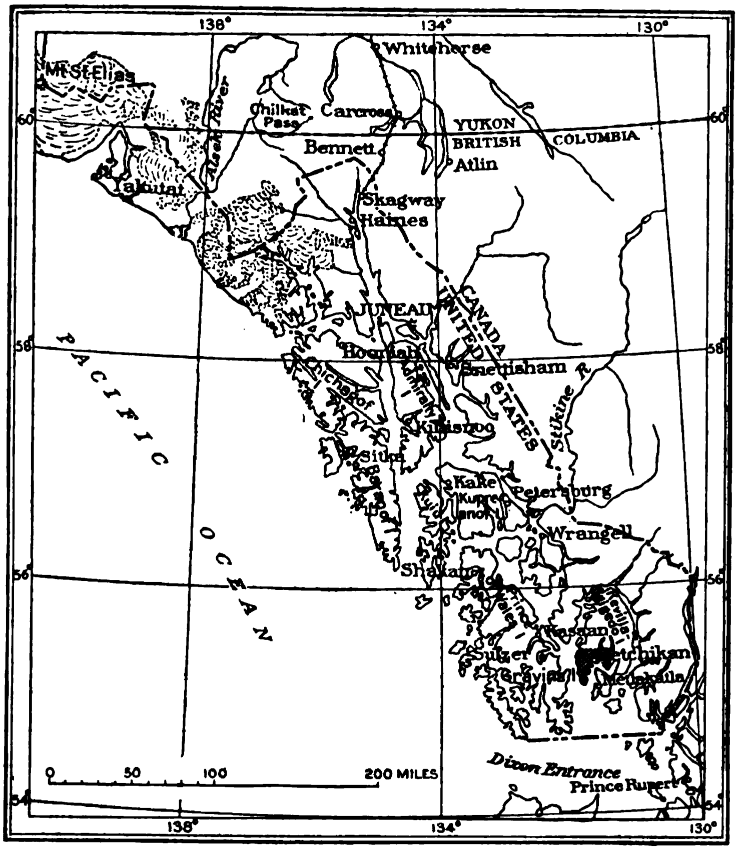

Figure 10.—Map of southeastern Alaska showing position of Gravina and Revillagigedo Islands.

LOCATION.

The area under discussion is included within the Ketchikan district, which lies in the southern part of southeastern Alaska, the panhandle strip of Alaska extending along the seaboard from Mount Fairweather to Dixon Entrance. Southeastern Alaska is composed of a mainland area and a fringe of islands known as Alexander Archipelago. The Ketchikan district lies wholly within the Pacific Mountain system, a geographic province which, as defined by

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[1] Notes on the geology of Gravina Island, Alaska: U. S. Geol. Survey Prof. Paper 95, pp. 97-105, 1915.

Brooks,[1] includes a broad zone of ranges forming a concave belt parallel to the southern coast of Alaska.

SURFACE FEATURES.

PHYSIOGRAPHIC PROVINCES.

Physiographically the Ketchikan district falls naturally into three main provinces. One comprises essentially the mainland area and adjacent islands. It includes the Coast Range and may be denominated the Coast Range or mainland province. The eastern or Prince of Wales Province comprises Prince of Wales Island and the islands to the west. Between these two mountainous areas lies an intermontane lowland province including Clarence Strait, Revillagigedo Channel, and Behm Canal and low-lying areas along their shores.

The dominating feature of the mainland province is the Coast Range, a high mountain mass with elevations of 7,000 to 8,000 feet. Brooks [2] describes it as follows:

> The Coast Range extends from near the boundary of Washington northward through British Columbia into southeastern Alaska, where it lies partly in Alaska and partly in Canadian territory. Following the coast line for nearly 900 miles it passes inland behind the St. Elias Range near the head of Lynn Canal. Thence it can be traced northward, decreasing in altitude and gradually losing definition until it finally merges with the interior plateau near Lake Kluane, in longitude 130° 30′. This range has no well-defined crest line but is rather a complex of irregular mountain masses occupying a coastal strip between the Pacific Ocean and the Central Plateau region.

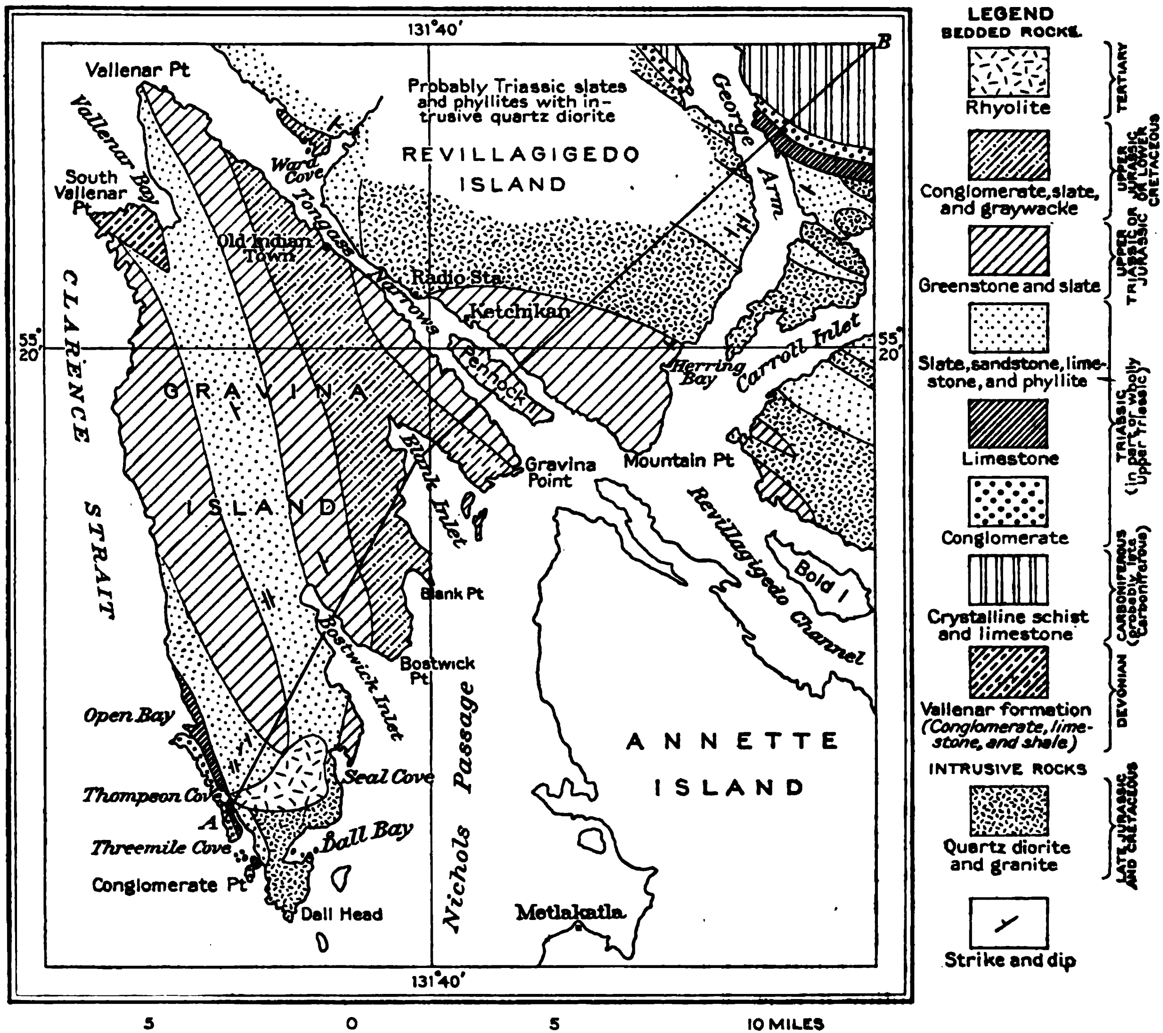

FIGURE 11.—Geologic sketch map of Gravina Island and a part of Revillagigedo Island, Alaska.

The Prince of Wales physiographic province is dominated by a complex group of short, rugged ranges reaching elevations of about 4,000 feet. In the northern part of the Alexander Archipelago these are not sharply differentiated from the Coast Range and were regarded by Brooks as a southeastern extension of the St. Elias Range.[1] In the Ketchikan district, however, as has been pointed out, the Prince of Wales mountainous region is quite distinct from the Coast Range, from which it is separated by the lowland province. It is correlated with the Vancouver Range, named by Dawson [2] and consisting of "an irregular mountain system which in its submerged parts constitutes Vancouver Island and the Queen Charlotte Islands."

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[1] Brooks, A. H., Preliminary report on the Ketchikan mining district, Alaska: U. S. Geol. Survey Prof. Paper 1, p. 14, 1902.

[2] Brooks, A. H., The geography and geology of Alaska: U. S. Geol. Survey Prof. Paper 45, p. 28, 1906.

The lowland province as here defined comprises the submarine area covered by the waters of Clarence Strait, Revillagigedo Channel, and Nichols Passage, and the bordering lowlands. This lowland is evidently a submerged portion of the Pacific coast downfold,[3] a series of basins forming a more or less continuous depression extending from the Gulf of California to British Columbia and Alaska. This lowland province would thus be correlated with Puget Sound and with the lowlands covered by the sound separating Queen Charlotte and Vancouver islands in British Columbia from the mainland. The area under discussion lies within and along the border of this lowland province, an area covered largely by Mesozoic sediments which apparently occupy an overturned synclinal fold.

GRAVINA ISLAND.

Gravina Island lies between Clarence Strait and Revillagigedo Channel and is separated from Revillagigedo Island by Tongass Narrows, a narrow, shallow channel a quarter of a mile to 2 miles wide and in places less than 100 feet deep. The island is roughly triangular. It has rather straight shore lines on two coasts, but the southeast coast is very irregular in shape, being broken by two deep bays, Blank and Bostwick inlets, and by minor indentations. The longest dimension of the island is 21 miles, and its maximum width is 9 miles. It has an area of about 100 square miles.

Gravina Island lies along the border line between the Coast Range and lowland provinces. Two low ranges of hills, the California Range and Dall Ridge, extend across the entire island from northwest to southeast. Dall Ridge reaches a maximum elevation of about 2,000 feet, and California Range of over 2,500 feet. Between these two ranges of hills, extending from Vallenar Bay to Bostwick Inlet, is a low depression only a few feet above sea level. Another depression extends from Blank Inlet to a point opposite Ward Cove. It lies between California Range and a low range that borders Tongass Narrows from Gravina Point northward for about 4 miles.

A striking parallelism exists between the ranges of hills, the intervening valleys, and the large bays—Vallenar, Bostwick, and Blank inlets. All have a dominant northwesterly direction, approximately parallel to the structure of the bedrock, which has evidently been the controlling factor in the topographic development.

REVILLAGIGEDO ISLAND.

Revillagigedo Island, with the exception of a fringe of lowland along Tongass Narrows, belongs to the mainland province. It is a large island of 1,120 square miles separated from the mainland by Behm Canal, a semicircular fiord that borders the northern part of the island. The interior of the island is high and rugged, its peaks reaching elevations of 4,000 feet. Three long fiords—Thorne Arm, Carroll Inlet, and George Inlet—break the southern coast into irregular-shaped peninsulas.

SUMMARY OF FORMATIONS AND STRUCTURE.

The rocks of Gravina Island and that portion of Revillagigedo Island included in this discussion are essentially Mesozoic formations that rest unconformably upon Carboniferous and Devonian rocks (fig. 11). The Mesozoic formations include three distinct terranes, all of which are fossiliferous. The lower and upper terranes, which are dominantly sedimentary, are respectively Triassic and either Upper Jurassic or Lower Cretaceous. The terrane of intermediate stratigraphic position, composed of volcanic rocks and intercalated sediments, contains fossils of Upper Jurassic or Lower Cretaceous age but may include also Triassic rocks. Tertiary lava flows occur on the southern part of Gravina Island but are not widely distributed. The most recent formations are marine glacial deposits that lie above the present high tide.

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[1] Brooks, A. H., The geography and geology of Alaska: U. S. Geol. Survey Prof. Paper 45, p. 29, 1906.

[2] Dawson, G. M., Roy. Soc. Canada Proc. and Trans., vol. 8, sec. 4, p. 4, 1890.

[3] Willis, Bailey, U. S. Geol. Survey Geol. Atlas, Tacoma folio (No. 54), p. 1, 1899.

The intrusive rocks of the Ketchikan region comprise for the most part the dioritic and granitic rocks of the Coast Range. They are not, however, confined to the Coast Range but occur in large bodies on the islands. The age of these intrusives is regarded as late Jurassic and Cretaceous.

The following table shows the correlation of the Mesozoic formations of Gravina Island with those of Graham and Vancouver islands as described by Canadian geologists:

Island Triassic conglomerate, limestone, and black slate are overlain by volcanic rocks and intercalated sediments of Triassic or Jurassic age, which, in turn, are overlain by the slate and graywacke of Blank Inlet, determined to be Jurassic or Cretaceous. Succeeding the Jurassic or Cretaceous sediments are volcanic rocks, with black slates and tuffs. Here the section is interrupted by a boss of granite, beyond which are black slates and phyllites, limestone, and schistose conglomerate. Beyond the conglomerate occur crystalline schists and massive semicrystalline limestone-bearing fossils regarded as certainly Paleozoic and probably Carboniferous. This anomalous position of the Paleozoic and Mesozoic rocks is probably due to an overturned position of one limb of the syncline.

Correlation table of Mesozoic formations of Gravina, Graham, and Vancouver islands.

Age.	Gravina Island.	Graham Island.[a]		Vancouver Island.[b]	
		Formation.	Lithologic character.	Formation.	Lithologic character.
Upper Cretaceous.		Queen Charlotte series.	Fossiliferous shales and conglomerates, with coal.	Nanaimo series.	Conglomerates, sandstones, and shales, with coal.
Lower Cretaceous.	Conglomerate, sandstone, and graywacke.				
Upper Jurassic.	Quartz diorite, etc.	Batholithic intrusives, etc.	Quartz diorite, etc.	Batholithic and dike intrusives.	Granodiorites, quartz diorites, etc.
Middle Jurassic.	Volcanic flows and tuffs with intercalated sediments. Volcanic breccias.	Yakoun formation.	Agglomerates, tuffs, and flows.	Sicker series (Jurassic or Triassic).	Andesitic flows and tuffs; schistose, slaty, tuffaceous, and quartzose sediments.
Lower Jurassic.		Maude formation.	Dark-colored, fine-grained, thinly laminated fossiliferous argillites, grading upward into tuffs and agglomerates. Possibly detrital conglomerates at base.	Sutton formation, Vancouver volcanics.	Crystalline limestones, metamorphic andesites, and pyroclastic rocks.
Upper Triassic.	Conglomerate, limestone, sandstone, and slate.				

[a] Mackenzie, J. D., Canada Geol. Survey Mem. 88, 1916.

[b] Clapp, C. H., Canada Geol. Survey Mem. 13, 1912.

Across the area including Gravina Island and the southern part of Revillagigedo Island the beds present a dominant northwest strike and, except locally, dip northeast, giving the appearance of simple monoclinal structure over a wide area. (See fig. 12.) These beds, however, are believed to represent overturned and truncated isoclinal folds and thus give the impression of a much greater thickness of sediments than really exists. The evidence for this conclusion lies in the following observed facts. On the southwest coast of Gravina

From the slate and graywacke area of Blank Inlet the general sequence of rocks is the same toward the northeast as it is toward the southwest, and it is believed that the similar rocks are in fact the same beds exposed on two limbs of an overturned fold, the trough of which is exposed on Blank Inlet. The volcanic rocks on each side of the Blank Inlet area of slate and graywacke are similar and may be correlated, as there is little reason to doubt their identity. The slates and phyllites of Revillagigedo Island are much more schistose than the black slates and sandstones of Gravina Island, with which they are correlated, but this is evidently due to the contact metamorphism caused by the adjoining intrusive granite. The other sediments of Revillagigedo Island are also more metamorphosed than their supposed equivalents on Gravina Island. The limestone is crystalline and the conglomerate is schistose, but these differences in metamorphism are also easily accounted for, not alone by the small body of granite shown in the sketch but also by the immense batholith of the Coast Range.

Along this eastern limb of the syncline is a greatly disturbed belt which apparently continues the entire length of southeastern Alaska along the border of the intrusives of the Coast Range. In this disturbed belt the folding is much more close, and the beds are more tightly compressed and, if correctly interpreted, are in part overturned. The structural form is not a simple syncline and might more correctly be termed a synclinorium, for one prominent anticline and a number of minor folds occur, the details of which are brought out more fully in the discussion of the different formations.

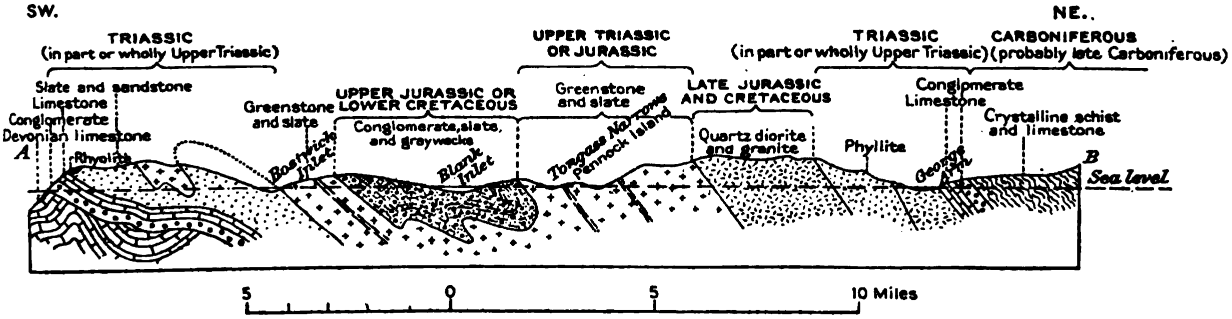
SW.
NE..
TRIASSIC
(in part or wholly Upper Triassic)
UPPER TRIASSIC OR JURASSIC
TRIASSIC
(in part or wholly Upper Triassic)
CARBONIFEROUS
(probably late Carboniferous)
Slate and sandstone
Limestone
Conglomerate
Devonian limestone
A
Rhyolite
Greenstone and slate
UPPER JURASSIC OR LOWER CRETACEOUS
Conglomerate, slate, and graywacke
Bostwick Inlet
Blank Inlet
Greenstone and slate
Tongass Narrows
Pennock Island
LATE JURASSIC AND CRETACEOUS
Quartz diorite and granite
Phyllite
Conglomerate
Limestone
George Arm
Crystalline schist and limestone
B
Sea level
5
0
5
10 Miles

Figure 12.—Structure section across Gravina and Revillagigedo islands, Alaska.

DEVONIAN ROCKS.

VALLENAR FORMATION.

DISTRIBUTION AND CHARACTER.

The oldest rocks recognized by the writer are the Devonian beds exposed on the west coast of Vallenar Bay, on Gravina Island. They consist of conglomerate, limestone, calcareous shales, sandstone, and argillites. The conglomerate is composed of cobbles of schist, quartz, and limestone embedded in a schistose matrix. The conglomerate is in part interbedded with thin limestones, calcareous shales, argillites, and sandstones containing Devonian fossils.

STRUCTURE AND STRATIGRAPHY.

The structure and stratigraphic relations of the Devonian beds are not clear. The beds are closely folded and deformed, and the relations are obscured by movement along the contacts. From South Vallenar Point eastward the beds trend dominantly northwest and dip northeast at varying angles. From the present position of the beds the base of the formation appears to be the conglomerate, which apparently rests upon the Mesozoic volcanic beds of the west coast of the island. This anomalous condition indicates an overturned position of the beds.

On the west coast of Vallenar Bay, about a mile east of South Vallenar Point, is the crest of a very sharply folded anticline (Pl. VIII, *D*), which has involved the calcareous shales and argillites. It is believed that these are the lowest of the Devonian beds and that the limestones and conglomerates to the west are stratigraphically higher in the section and occupy the overturned limb of a steeply pitching anticline that is overturned toward the west. It may be that the schistose conglomerate containing an abundance of limestone cobbles is a member of the Mesozoic greenstone and intercalated sedimentary beds. The contact with the Mesozoic beds at the head of Vallenar Bay is covered by gravels. This anticline along which the Devonian beds are brought to the surface on Vallenar Bay is presumably the same fold that extends along Dall Ridge to Seal Cove and forms a minor fold in the broad synclinorium involving all the rocks between the west coast of Gravina Island and George Arm.

AGE AND CORRELATION.

The Devonian rocks of Vallenar Bay were first described as the Vallenar "series" by Brooks,[1] who states:

> The Vallenar series [is] so named from its type exposures on Vallenar Bay, at the northern end of Gravina Island. The series is composed essentially of limestones and calcareous schists with some black slates.

Fossils were collected at this locality by Brooks in 1901 and determined by Charles Schuchert as Devonian. More collections were made in 1905 and 1906 by the Wrights and E. M. Kindle [2] who report:

> *One mile west of Vallenar Bay, Gravina Island.*—The material from this locality, while generally insufficient for specific determination, is much better than that obtained last year (1905) and leaves no doubt as to the Devonian age of the beds west of Vallenar Bay. Several specimens of *Atrypa reticularis* are present. This fixes the horizon as not later than Carboniferous, while the association of *Chonetes* cf. *manitobensis*, *Spirifer* sp., *Proetus* sp., and *Cyclonema* sp. indicate a horizon of Devonian age, probably middle Devonian.

Some poorly preserved material collected by the writer in 1915 was determined by T. W. Stanton as probably Devonian.

The beds of Vallenar Bay were correlated by Brooks with rocks on Long Island.[3] Middle Devonian rocks of similar character occur on Clover Bay, on the east coast, and Hunter Bay and Klakas Inlet, on the west coast of Prince of Wales Island and on Hotspur Island.

CARBONIFEROUS ROCKS.

BEDS INCLUDED.

The term "Ketchikan series" was applied by Brooks [4] to argillaceous and carbonaceous rocks with some limestone beds and finely foliated slates and phyllites that occur on Tongass Narrows, near Ketchikan, on Revillagigedo Island, and on Cleveland Peninsula. Brooks considered these rocks to be in part Carboniferous and in part Mesozoic and suggested that probably the limestones are Carboniferous and the slates are Triassic.

The Wrights [5] state:

> In view of the comparatively weak paleontologic and stratigraphic evidence bearing on the precise age of these argillites and crystalline schists, it is possible that their period of deposition extended even beyond the Carboniferous period into the Triassic, especially when the extensive development of Triassic strata to the south in British Columbia, as described by G. M. Dawson, is taken into consideration. The evidence thus far gathered, however, indicates Carboniferous age for the greater portion of these crystalline schists and argillites.

Brooks noted that the limestones overlie the argillites (slate and greenstone) and thus appear to be younger. This confusion was due to their overturned position, the older beds actually overlying the younger ones.

The assignment of the rocks mapped by Brooks as the "Ketchikan series" to both Carboniferous and Triassic is in harmony with the writer's interpretations. The part of Brooks's "Ketchikan series" that stratigraphically underlies the conglomerate and massive limestone which in this report are correlated with the Upper Triassic rocks of Gravina Island is here regarded as Carboniferous.

DISTRIBUTION AND CHARACTER.

The rocks herein assigned to the Carboniferous are essentially crystalline schists and limestone. In areal distribution they occupy a broad belt along the border of the Coast Range, extending from the mouth of Portland Canal northwestward for an unknown distance. In the area under discussion they are restricted to a small area on Revillagigedo Island near the head of George Arm. The schists make up the greater part of the series. They are evidently the result of contact metamorphism induced by the intrusive rocks. An adequate description of them would require a detailed petrographic study of the rocks in the field and an intensive microscopic study, neither of which has been made by the writer. The limestone constitutes a relatively small part of the series. It occurs in beds 100 feet in maximum thickness intercalated with the crystalline schists. It is dominantly white and crystalline.

STRUCTURE AND STRATIGRAPHIC RELATIONS.

The Carboniferous rocks are closely folded and contorted. They occupy a greatly disturbed belt along the western border of the Coast Range and form the overturned limb of a synclinorium in which are involved all the formations east of Clarence Strait. The other limb of the syncline comes to the surface on the western coast of Gravina Island.

The base of the Carboniferous schists and limestones is not exposed. They apparently

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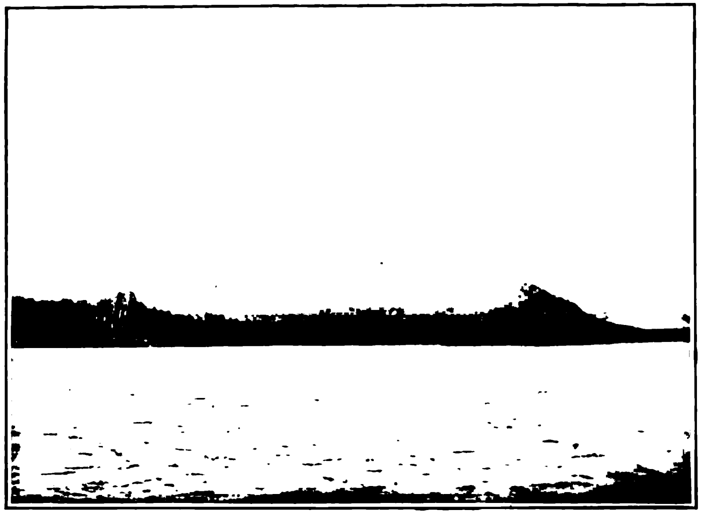
[1] Brooks, A. H., Preliminary report on the Ketchikan mining district, Alaska: U. S. Geol. Survey Prof. Paper 1, p. 42, 1902.

[2] Wright, F. E., and C. W., The Ketchikan and Wrangell mining districts, Alaska: U. S. Geol. Survey Bull. 347, p. 50, 1908.

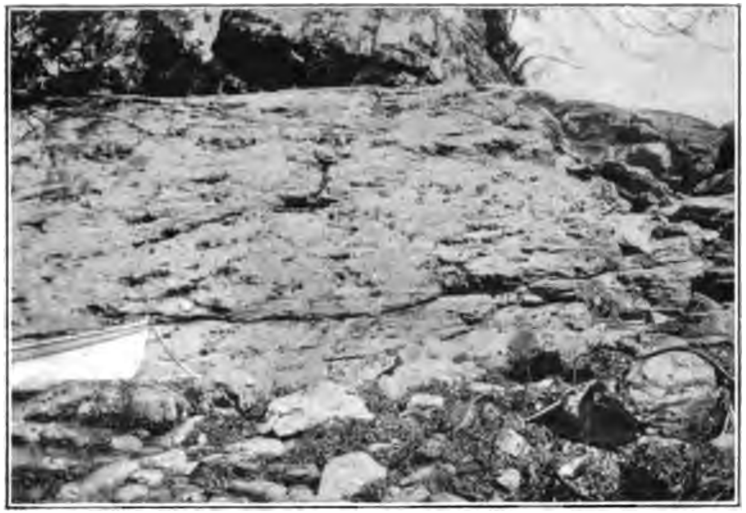
[3] Brooks, A. H., op. cit., p. 43.

[4] Brooks, A. H., Preliminary report on the Ketchikan mining district, Alaska: U. S. Geol. Survey Prof. Paper 1, p. 44, 1902.

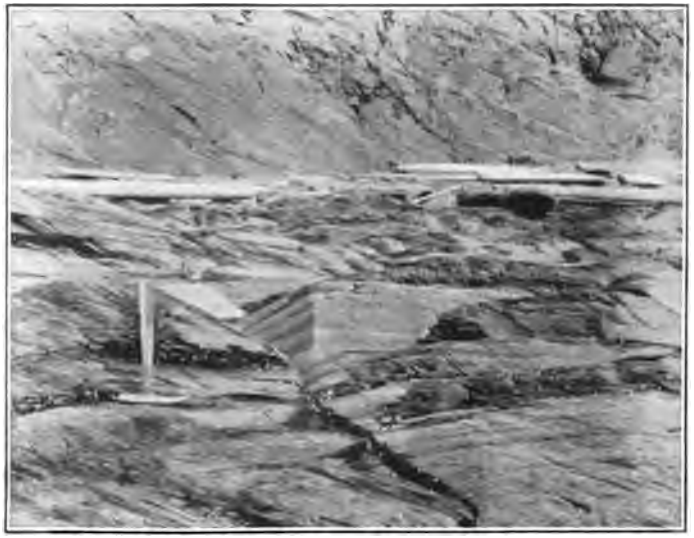
[5] Wright, F. E. and C. W., op. cit., p. 56.



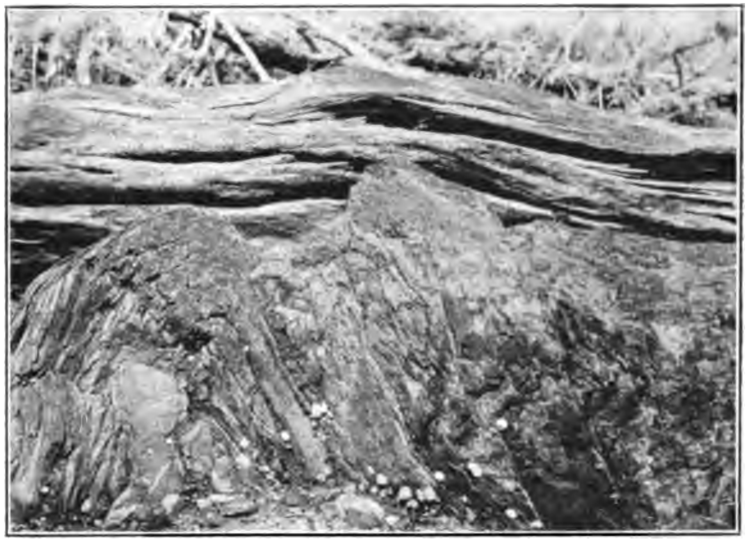
A. WAVE-CUT BENCH, DALL BAY, GRAVINA ISLAND, ALASKA.



B. CONGLOMERATE, BLANK INLET, GRAVINA ISLAND.



C. SLATE AND GRAYWACKE, BLANK INLET, GRAVINA ISLAND.



D. ANTICLINE ON VALLENAR BAY, GRAVINA ISLAND.

overlie conglomerate and limestone beds whose age is unknown but which are regarded as Upper Triassic. The strata at this locality, however, are believed to be overturned so that the normal sequence of the beds is reversed. (See fig. 12.)

AGE AND CORRELATION.

Fossils were collected from the limestone near Coon Island at the head of George Arm by Mr. Brooks, who states that the many crinoid stems suggest that at least the limestones belong to the upper Paleozoic. C. W. Wright also collected fossils from George Arm, on which E. M. Kindle reports as follows:[1]

> *No. 966. Point on southeast side of George Inlet 10 miles from its head, Revillagigedo Island.*—The fossils from this point comprise only crinoid stems, which, however, are so abundant as to make up a large portion of the rock. Crinoid stems can not ordinarily be used for correlation. However, their great abundance here seems to justify a surmise that they very probably represent a Carboniferous horizon. Crinoids in such abundance as is shown by these specimens occur in very few places, if anywhere, outside of Carboniferous horizons. In the absence of other evidence the horizon represented may be referred tentatively to the Carboniferous.

Other collections made by P. S. Smith in 1913 contained nothing of determinative value but were considered as probably Paleozoic. No collections were made by the writer, but the crinoid-bearing beds were observed at a number of places.

There is little doubt of the Carboniferous age of at least one of the fossiliferous beds in this series of schists and limestones, but their exact age and stratigraphic position are much in doubt. Lithologically, except in amount of metamorphism, they resemble the slate and limestone of the Porcupine district. The slates and limestone beds of the Porcupine district are not fossiliferous, but from closely associated massive limestone beds fossils were collected which G. H. Girty first doubtfully referred to the lower Carboniferous but later determined as upper Carboniferous. Regarding a similar fauna from Admiralty Island, Girty[2] says:

> The fauna from point at southeast entrance to Pybus Bay, Admiralty Island, which also seems to occur at point on divide between Chapin Bay and Herring Bay, Admiralty Island, is without doubt upper Carboniferous in age and probably can be designated Permo-Carboniferous. This fauna is known to be at but one other point in Alaska—Porcupine mining district—where some of the same species were obtained last year. This fauna also is entirely dissimilar from those of the Mississippi Valley and Appalachian region and finds nearer affinities in those of western United States and of eastern Europe (Russia).

These schists and limestones are therefore tentatively regarded as late Carboniferous. Their relation to the Devonian beds of Vallenar Bay is not evident, as the two are nowhere known to be in contact. If these schists and limestones are correctly correlated with the late Carboniferous it would appear that there is lacking in this region a very thick section of Carboniferous rocks which are widely developed on the west coast of Prince of Wales Island. These include Mississippian limestone and cherts, which are probably the equivalent of the Lisburne limestone, and Pennsylvanian limestones that include Moscovian and Gschelian faunas.

TRIASSIC ROCKS.

BEDS INCLUDED.

The term "Gravina series" was first applied by Brooks[3] to massive conglomerate overlain by black slates or shales occurring on the south end of Gravina Island. He included in his mapping of this "series" the somewhat similar massive conglomerates and associated black slates and arenaceous sediments of the west coast, Bostwick Inlet, and Blank Inlet and suggested its probable extension to other places. As a result of recent investigations, however, the sedimentary rocks of Gravina Island originally defined as the "Gravina series" are now known to include two sedimentary formations—one of Triassic age and one of Jurassic or Cretaceous age. These two sedimentary formations are associated with volcanic rocks of intermediate stratigraphic position. Brooks first regarded the "Gravina series" as Cretaceous and correlated it with the Queen Charlotte series of Vancouver and Queen Charlotte islands, but later he stated that its identity with the "Vancouver series" (Triassic) seemed equally probable.[4] His correlations with both Triassic and Cretaceous formations, made without any fossils, proved substantially correct.

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[1] Wright, F. E. and C. W., op. cit., p. 55.

[2] U. S. Geol. Survey Bull. 287, p. 143, 1906.

[3] Brooks, A. H., Preliminary report on the Ketchikan mining district, Alaska: U. S. Geol. Survey Prof. Paper 1, p. 45, 1902.

[4] Brooks, A. H., The geography and geology of Alaska: U. S. Geol. Survey Prof. Paper 45, p. 226, 1906

DISTRIBUTION AND CHARACTER.

The Upper Triassic rocks on Gravina Island comprise a gradationally conformable series of conglomerates, limestones, sandstones, and slates. They are most typically exposed on the southwest coast of the island, where they occupy a narrow belt that extends from a small cove opposite Dall Bay northwestward for about 7 miles. Unfossiliferous rocks, presumably of the same formation, to judge from lithologic similarity and structural relations, occupy a narrow belt that extends across George Arm and Carroll Inlet.

On Gravina Island the Upper Triassic rocks fall naturally into three main divisions—one composed essentially of conglomerate, one essentially of limestone, and one of interbedded black slate, sandstone, conglomerate, and limestone. These three conformable terranes are shown by fossils to be probably Upper Triassic. Overlying the Upper Triassic sediments, with apparent conformity, are volcanic agglomerates and intercalated sedimentary beds which are, at least in part, of Upper Jurassic or lower Cretaceous age and possibly in part of Upper Triassic age.

The exposed basal member of the series on Gravina Island is a coarse conglomerate that extends along the southwest coast of the island from Conglomerate Point northwestward to Open Bay and occupies three narrow strips whose continuity is broken by Fivemile Cove, Thompson Cove, and Threemile Cove. The conglomerate is a heavily bedded, massive rock. The boulders are essentially of angular coarse-grained granite resembling the granite of Annette Island, and the matrix is quartz-feldspar sand presumably derived from the same source as the boulders. Intercalated with the coarse conglomerate are thin beds of sandstone, which are composed of the same material as the matrix of the conglomerate, and gradational beds of grits. Thin beds of fossiliferous limestone and black slate with pronounced cleavage occur sparingly. The conglomerate and intercalated sandstone beds are strongly indurated and break with prominent fractures across the boulders.

On a small cove south of Threemile Cove[1] the conglomerate is finer grained toward the top and passes upward into grits, sandstone, and slate which are overlain by a large block of fossiliferous massive limestone. There has been some movement along this contact, so that the relations are confused, but the limestone is apparently above the conglomerate and sandstone. On Thompson Cove the conformable relations of the limestone to the conglomerate, sandstone, and slate are more evident, although here also there has been some faulting.

In the upper part of the conglomerate the beds are thinner and the material is much finer grained and contains more sandstone, slate, and thin beds of limestone, which are conformably overlain by the massive limestone.

The limestone varies in appearance from place to place. On Thompson Cove and Open Bay it is a soft gray fossiliferous rock, corals being especially abundant. On Threemile Cove it is more closely folded, is considerably silicified, and weathers out brick-red. The limestone here is less fossiliferous, and the fossils are poorly preserved. The greater amount of deformation of the limestones on Threemile Cove is probably the result of contact metamorphism induced by the intrusive rocks of Dall Head.

The massive limestone is conformably overlain by a great thickness of black slate with intercalated beds of conglomerate, sandstone, and limestone. These beds crop out along the coast of Gravina Island for a distance of about 3 miles north of the limestone area and extend to the high hills of Dall Ridge north of Dall Head. Similar rocks are exposed on Bostwick Inlet and Seal Cove and extend northwestward in a belt from 2 to 3 miles wide to Vallenar Bay and North Vallenar Point.

The dominant rocks of this series are black-clay slates having a pronounced cleavage. Intercalated with the slate are thin beds of quartz sandstone, quartzite, and conglomeratic sandstone. The limestone beds are not numerous but are usually fossiliferous. The interbedded limestone layers are about 20 to 30 feet in thickness but appear to be lenticular.

The black slate and associated sediments are closely folded, especially on Threemile Cove, where the beds are thrown into sharp contorted folds. The beds on Vallenar Bay are much more regular and show none of the close folding.

On Revillagigedo Island associated conglomerate, limestone, schistose slates, and phyllites are correlated with the sedimentary series of Gravina Island on the basis of similarity of lithology and sequence and stratigraphic and structural relations. The beds are exposed on George Arm, Carroll Inlet, and Thorne Arm. The lithologic similarity of these rocks to the Triassic rocks of Gravina Island is marked, notwithstanding their more schistose nature, which is due to their proximity to the large masses of intrusive rocks. The conglomerate is very schistose, and the cobbles are mashed and deformed. The limestone is white and crystalline, and the slates are in part schistose and might more correctly be termed phyllites and schists. Similar slates, phyllites, and schists occur on the north end of Tongass Narrows.

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[1] Threemile Cove has appeared in the literature as "cove 3 miles north of Dall Head."

These rocks show different degrees of metamorphism. The most extreme phases occur along the borders of the plutonic bodies of Revillagigedo Island, and the amount of metamorphism varies more or less directly with its nearness to the igneous rock. On Tongass Narrows the slates show little metamorphism except cleavage and the development of a little secondary mica. As the igneous rocks are approached the metamorphism becomes more noticeable. On Ward Cove the slates have a very pronounced schistosity and contain considerable secondary mica and hornblende. The most prominent type is a dark-gray rock with acicular hornblende crystals a centimeter in length, white mica, quartz, and colorless garnet in large euhedral crystals. Pyrite is locally abundant. Another type is a dark-green schist composed essentially of hornblende and quartz. Garnet is an abundant accessory. It occurs in euhedral crystals partly altered to calcite and quartz. Epidote, chlorite, and pyrite also occur.

No fossils have been found in these rocks, but on account of their stratigraphic position between the Carboniferous rocks of Revillagigedo Island and the supposedly Triassic or Jurassic volcanic rocks of Tongass Narrows and Gravina Island, they appear to occupy about the same horizon as the Triassic slates and sandstones of Gravina Island. The sequence of this series is also the same as the Triassic succession of sedimentary beds of Gravina Island—conglomerate, limestone, argillaceous and arenaceous sediments. From the present relation of the beds the sequence on the two islands appears to be reversed, but this is due to the overturned position of the section on Revillagigedo Island.

STRUCTURE.

The Triassic conglomerate, limestone, and black slate of the west coast of Gravina Island, although closely folded, maintain a general strike of about N. 70° W. The beds dip northeast and occupy one limb of the synclinorium, which dips beneath the volcanic rocks and comes to the surface in Bostwick Inlet and presumably also on Revillagigedo Island near the head of George Arm, where the beds are involved in the overturned limb of the synclinorium.

STRATIGRAPHIC RELATIONS.

The base of the Upper Triassic series of Gravina Island is not visible. The lowest part exposed occurs at Threemile and Thompson coves, where the actual base of the conglomerate is concealed by the water. At Vallenar Bay the Triassic rocks overlie Devonian sediments that come to the surface along the axis of an anticline. The contact is covered by the Quaternary deposits of Vallenar Bay. The presence of Devonian pebbles in the conglomerates of Threemile Cove indicates an underlying rock of that age, and on George Arm the supposedly Triassic rocks rest upon Carboniferous rocks. A marked unconformity at the base of the Upper Triassic rocks is thus evident.

On Gravina and Revillagigedo islands the Triassic rocks are in places conformably overlain by volcanic beds of Upper Triassic or Jurassic age and in places unconformably by slate and graywacke of Jurassic or Cretaceous age. The conglomerate and sandstone of Dall Head are invaded by dioritic rocks, presumably of Jurassic or Cretaceous age, and are unconformably overlain by Tertiary lavas.

ORIGIN.

The Upper Triassic rocks are the products of normal deposition and are evidently of marine origin, as shown by the fauna present in all the members. They are believed to represent an unbroken period of deposition, but the abrupt change from conglomerate to massive limestone and black slate with numerous intercalations of limestone, conglomerate, and sandstone indicates that the rocks were deposited under constantly changing conditions. The massive conglomerate was evidently a basal formation and was laid down in comparatively shallow water near the shore line and derived its material from the products of land waste. The organic nature of the limestone is clearly proved by the great abundance of organic remains, especially corals, which it contains. The schists and phyllites were originally slates and sandstones, probably of marine origin, but have been changed to their present condition by the contact influence of the intrusive rocks.

AGE AND CORRELATION.

The age of these rocks is shown by a large number of fossil collections, made from all members of the series, to be Triassic, probably Upper Triassic.

Fossils collected by G. C. Martin and K. M. Overbeck from the massive conglomerate at the exposed base of this series were determined by T. W. Stanton as follows:

8831 (G. C. M. No. 3). Gravina Island near 8830. Large limestone nodule in conglomerate. The whole nodule is a nautiloid with deeply lobed suture, possibly referable to *Cosmonautilus*. On the back is a *Rhynchonella* (?). Probably Triassic.

8833 (G. C. M. No. 5). Gravina Island, south arm of cove 3 miles north of Dall Head. Near zone of nodular masses of limestone in conglomerate. This lot appears to be Devonian.

Mr. Martin's opinion, with which the writer agrees, is that the Triassic conglomerate rests unconformably upon Devonian rocks, and the Devonian fossils from Threemile Cove were obtained either from boulders in the conglomerate or from unrecognized Devonian rocks occurring in complex structural relations with the Triassic beds. The beds on Threemile and Thompson coves are faulted and also closely folded and contorted, thus being thrown into complex structural relations. From the wording of the locality description given above it would appear quite possible that the fossils were collected from included masses of limestone in the conglomerate. In 1916 A. H. Brooks and the writer collected fossils from narrow bands of limestone definitely interbedded with the conglomerate. J. B. Reeside reports on these as follows:

9899 (16 ACh 136). Threemile Cove, Gravina Island. Echinoid spine, possibly of *Cidaris*. Age undetermined.

Fossils were first collected from Threemile Cove in 1906 by the Wrights.[1] The exact locality is uncertain, but the matrix of the fossiliferous rocks is described as calcareous schist, which is evidently the siliceous limestone. The fauna was regarded by G. H. Girty as coming from the uppermost part of the Carboniferous or from the Mesozoic. These beds were thus doubtfully referred to the Mesozoic for some years, but recent collections have shown them to be without much doubt Triassic and probably Upper Triassic.

Collections made by Martin and Overbeck from the limestone beds of Threemile Cove occurring beneath the black slate were determined by T. W. Stanton as follows:

8830 (G. C. M. No. 2). Gravina Island, south arm of "cove 3 miles north of Dall Head." Massive limestone outcrop near anchorage behind wooded island.
 Undetermined corals of Mesozoic type, two or three genera represented.
 Ostrea? sp.
 Pseudomelania? sp., internal cast.
 Arcestes?? sp., fragment; may not even be an ammonite.
 Probably Triassic.

8832 (G. C. M. No. 4). Gravina Island, near south foreland on arm of "cove 3 miles north of Dall Head," near contact with conglomerate.
 Undetermined coral fragment.
 Pentacrinus sp., segment of column.
 Probably Triassic.

8834 (G. C. M. No. 6). Gravina Island, north arm of "cove 3 miles north of Dall Head." Massive limestone in reef west of cabin. Probably about 100 feet below 8704.
 Corals, probably several genera.
 Cassianella sp.
 Myophoria?? sp.
 Natica sp.
 Murchisonia? sp.
 Triassic.

8835 (G. C. M. No. 7). Gravina Island, near 8834, from thin-bedded limestone interbedded with shale about 20 or 30 feet below 8834.
 Corals; several genera represented.
 Spiriferina? sp.
 Myophoria? sp.
 Natica sp.
 Turritella? sp.
 Pseudomelania? sp.
 Trachyceras? sp., small fragment.
 Triassic.

The following collections made by the writer in 1915 from the limestone overlying the massive conglomerate were determined by Mr. Stanton:

9531 (15 ACh 111). West coast of Gravina Island. Cove 2½ miles north of Dall Head.
 Echinoid spines.
 Undetermined corals.
 Ostrea? sp.
 Gryphaea? sp.
 Pecten sp.
 Natica? sp.
 Turritella? sp.
 The fossils in this lot are poorly preserved and mostly fragmentary. They are apparently Mesozoic and may be Triassic.

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[1] Wright, F. E. and C. W., op. cit., p. 52.

15 (ACh 121). Northeast shore of Thompson Cove, Gravina Island.

Corals, genus undetermined.
Pentacrinus sp.
Echinoid spine.
Ostrea? sp.
Solemya? sp.
Turritella? sp.
Spiriferina? sp.
Probably Triassic.

9534 (15 ACh 122). Northeast shore of Thompson Cove, Gravina Island.

This lot includes undetermined corals, Ostrea?, Turritella?, and undetermined gastropods. Probably Triassic.

9535 (15 ACh 123). North shore of Thompson Cove, Gravina Island.

Pecten? sp.
Gryphaea? sp.
Halobia sp.
Undetermined ammonite.
Triassic.

9536 (15 ACh 129). Fivemile Cove, Gravina Island. Limestone apparently overlying massive conglomerate.

Corals, several undetermined genera.
Bryozoa?
Pecten sp.
Purpurina?? sp.
Undetermined slender gastropod.
Probably Triassic.

9537 (15 ACh 130). Fivemile Cove, Gravina Island.

Corals, several genera.
Bryozoa?
Myophoria sp.
Purpurina?? sp.
Turbo? sp.
Triassic.

9538 (15 ACh 132). Fivemile Cove, Gravina Island, immediately north of 9537.

Gryphaea sp.
Probably Triassic.

Two lots of fossils collected by P. S. Smith from the black slate of Threemile Cove (8704) and also from Fivemile Cove (8705) were submitted to Mr. Stanton, who reported as follows:

> The only fossil species recognized in these two lots is a *Halobia*, which is closely related to if not identical with *H. superba* Mojsisovics, an Upper Triassic species. The rocks from which these collections came are therefore referred to the Triassic.

The writer made the following collections in 1915 from the black slate and interbedded limestone and sandstone beds of Threemile Cove, Thompson Cove, and Dall Ridge. Stanton reports:

15 ACh 112. Threemile Cove, Gravina Island, 300 yards north of 15 ACh 111.

Spiriferina? sp.
Halobia? sp.
Probably Triassic.

9532 (15 ACh 113). Threemile Cove, Gravina Island, 300 yards southeast of north end of cove and about 700 yards north of 15 ACh 112. Fossils from black slate and limestone.

The black slate shows fragmentary specimens of *Halobia* cf. *H. superba* Mojsisovics, of Upper Triassic age, while the limestone shows imperfect specimens which seem to be referable to *Aucella* and hence is probably of Upper Jurassic age.

The limestone and black slate from which the fossils regarded as Upper Triassic and Upper Jurassic were obtained are apparently interbedded. This anomalous occurrence may be due to very closely infolded Jurassic rocks, but it appears more probable that the doubtful Jurassic forms are not correctly identified.

9533 (15 ACh 115). Thompson Cove, Gravina Island. Halobia slates in fault block.

Cidaris? sp., imprint of surface.
Halobia cf. H. superba Mojsisovics.
Triassic.

15 ACh 124. Dall Ridge, 1 miles north of Dall Head, Gravina Island.

Echinoid spines, etc.
Probably Triassic.

The following collection was identified by J. B. Reeside:

9900 (16 ACh 137). Threemile Cove, Gravina Island.

Cerithium? sp., fragment showing part of two whorls.
Isastraea cf. I. profunda Reuss.
Thamnastraea cf. T. rectilamellosa Winkl.
Spongiomorpha? sp.
Hydrozoan, undetermined.
Natica? sp.
These forms are apparently of the Upper Triassic coral fauna referred by J. P. Smith to the Noric.

The conglomerate sandstones near the crest of Dall Ridge contain Devonian fossils, but as these are fragmentary and occur in pebbles they indicate nothing more than the post-Devonian age of the rocks. Kirk reports:

15 ACh 126. Dall Ridge, 4 miles north of Dall Head.

Fragmental fossils apparently occurring as pebbles in conglomerate. At least one of the fossils is Devonian. It is a coral, probably *Alveolites*.

Black slates and sandstones exposed on the west coast of Bostwick Inlet are correlated, on structural grounds and lithologic similarity, with the upper part of the Triassic rocks on the west coast of the island, but fossils collected by different men have served to confuse the relations. The fossils listed below were collected in 1914 by Martin and Overbeck from the west shore of Bostwick Inlet and identified by T. W. Stanton:

8836 (G. C. M. No. 8). Gravina Island, Bostwick Inlet, west shore near entrance. From angular nodules in a brecciated (?) nodular limestone.

Terebratula sp.
Spiriferina? sp.
Pecten sp.
Plicatula? sp.
Cassianella sp.
Myophoria sp.
Myophoria or Trigonia sp.
Nacula sp.
Astarte? sp.
Arcestes? sp.

Triassic. This assemblage suggests the fauna of the lower part of the Modin formation in California, which was tentatively assigned to the Jurassic.

Near this same locality P. S. Smith[1] also collected fossils on which Girty reports as follows:

> Three lots from Bostwick Inlet, Gravina Island, contain round crinoid stems (13AS170) and a single compressed pelecypod (13AS169), suggesting the genus *Posidonomya*. The third lot (13AS171) contains a pelecypod fauna interesting and varied but entirely new to me. As these fossils at best show only the shapes and some of them the sculpture, and as pelecypods of similar external appearance may belong to widely different genera, the identifications made here are offered with doubt. Though similar doubt tacitly surrounds many pelecypod identifications in faunal lists and elsewhere, I have expressed it in this case by the use of question marks because the age of the whole fauna is involved in such uncertainty. In lot 171 five types are represented more or less abundantly and by specimens more or less good. These are *Glossites?* cf. *G. lingualis*, *Schizodus?* cf. *S. appressus*, *Paracyclas?* cf. *P. ellipticus*, *Crenipecten?* cf. *C. crenulatus*, *Elymella?* cf. *E. nuculoides*. Besides these, however, there are a good many indeterminate forms, some of which suggest the genera *Leda*, *Chonetes??*, *Pseudomonotis??*, *Aviculipecten*, and *Nucula*. The age of the fauna is quite uncertain. You declined for the time being to admit it into the Triassic, and nothing resembling it has thus far been brought in from the Alaskan Carboniferous. The generic and specific resemblances suggested above might indicate a Devonian fauna, but neither has any Devonian fauna related to this been obtained from Alaska. The genus *Chonetes*, if definitely present, would at least limit the geologic age to the upper Paleozoic, but the specimen is so imperfect that even the identification as a brachiopod is doubtful.
>
> Thus the age of this, the best fauna in the collection, must for the present remain undesignated. It would be highly rash to attempt any definite age determination or conclusion for the other lots, containing, as they do, for the most part, only crinoid stems (even that being doubtful in some cases), though they may tentatively be placed in the Paleozoic.

Regarding this report Smith suggests that this doubtfully determined fauna from Bostwick Inlet, which is unknown elsewhere in Alaska, may mark a Lower Triassic horizon, also unknown in Alaska. He states:

> As Mr. Girty points out, this fauna is entirely unlike any other from Alaska. It therefore affords little aid in solving the stratigraphic position of the beds on Gravina Island. Certain significant deductions, however, suggest themselves. In general in southeastern Alaska the known Carboniferous rocks are limestones and not lithologically similar to the rocks of Gravina Island. The rocks here discussed are much less dynamically metamorphosed and are less intensely deformed than the known Devonian or Carboniferous rocks of the region. Their relation to the andesitic agglomerates and flows fits in better with an assumed Mesozoic age than with a Paleozoic age. The almost uninterrupted succession of beds from a basal (?) conglomerate to shales containing unquestioned Triassic fossils on the southwestern coast suggests that the doubtfully determined genera from that locality, provisionally assigned to the Carboniferous, justify the suggestion made by Mr. Girty at that time that they may mark a Triassic horizon. No Lower Triassic is known in Alaska. Is it not possible that this fauna from Bostwick Inlet, which is unknown elsewhere in Alaska, fits into this as yet unfilled gap?

Its reference to the Lower Triassic, however, seems improbable, for the fauna is in the upper part of the formation, above the position of the *Halobia*-bearing slates (determined as Upper Triassic) and immediately below the Upper Jurassic or Lower Cretaceous volcanic rocks. Its reference to the Upper Triassic or the Lower or Middle Jurassic would be more in keeping with the observed relations.

The term "Vancouver series" was first applied by Dawson[2] to the entire mass of volcanic materials and interbedded limestones, flaggy argillites, and quartzites that unconformably underlie the Cretaceous rocks of Vancouver Island. At that time, on the evidence of intercalated fossiliferous beds, this series of rocks was regarded as largely Triassic, although the possibility of its including both Jurassic and Carboniferous rocks was recognized. The "Vancouver series" was later subdivided by Clapp,[3] who has shown that it is in part Jurassic and possibly also Carboniferous. The Triassic rocks of Gravina Island are probably the equivalent of parts of the "Vancouver series" of Vancouver and Queen Charlotte islands.

Triassic rocks are widespread throughout Alaska and occur at many places in southeastern Alaska. Fossils of Upper Triassic age have been found on Admiralty, Kupreanof, and Screen islands.

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[1] Notes on the geology of Gravina Island, Alaska: Prof. Paper 95, p. 103, 1915.

[2] Dawson, G. M., Canada Geol. Survey Ann. Rept. 1886, p. 10B.

[3] Clapp, C. H., Southern Vancouver Island: Canada Geol. Survey Mem. 13, p. 37, 1912.

Martin[1] states that the abundant corals in some of these Triassic rocks of Gravina Island suggest that they may represent the lower Noric coral fauna of Iliamna Lake. He considers that the Triassic limestones of southeastern Alaska, which in general are characterized by faunas containing *Halobia* cf. *H. superba* Mojsisovics, correspond at least approximately in position to the Chitistone limestone of the Copper River valley.

UPPER TRIASSIC OR JURASSIC ROCKS.

The rocks designated greenstone and slate on the map are made up of an interbedded series of altered tuffs, flows, and black slates, with some intrusives, occurring on Gravina and Revillagigedo islands. The greenstones and slates overlie the Upper Triassic rocks with apparent conformity. On the evidence of a few fossils found in the intercalated sediments and on structural grounds and analogy with rocks of known age these rocks are regarded as Upper Triassic or Jurassic.

DISTRIBUTION.

The greenstone and slate occupy three parallel belts on Gravina Island. One extends from South Vallenar Point to Seal Cove, another from the east shore of Bostwick Inlet to Vallenar Point, and the third along Tongass Narrows from Old Indian Town to Gravina Point. Northeast of Tongass Narrows similar rocks extend from Radio station to Herring Bay.

CHARACTER AND STRATIGRAPHIC RELATIONS.

The rocks consist essentially of volcanic breccias and tuffs with interbedded black slates and water-laid fine-grained tuffaceous sediments. Certain green schistose tuffs apparently interbedded with the more massive tuffs and breccias may be older infolded rocks, and some graywackes and slates may be younger infolded rocks.

The detailed sequence of the volcanic rocks of Gravina Island has not been worked out. In general they may be divided into two parts—a lower series of purely igneous material, mainly coarse pyroclastic rocks and breccias and an upper series of mixed water-laid tuffs and black slates and limestone, with porphyritic basic rocks of similar composition, evidently partly intrusive and partly explosive. No sharp line separates the two parts, which the writer has not differentiated on the geologic map. The black slates pass into green fissile tuffs, and these into more massive varieties, so that as a rule a sharp line of contact can not be drawn between them. By more detailed work the lower purely volcanic material might be separated from the upper mixed sedimentary and igneous material. The limestone bodies are too small to be shown on a map.

The base of the volcanic rocks is evidently the coarse breccia that overlies the Upper Triassic sediments of the west coast of Gravina Island. This breccia occupies the southern part of Dall Ridge and portions of California Ridge. It is a fine-grained green rock with large angular fragments set in a dense matrix of the same composition.

The breccia passes upward into finer-grained tuffs, in part at least water-laid material with which are intercalated black slates and thin beds of crystalline limestone. The black slates are typical clay slates having a well-developed cleavage, with bedding planes discernible in places. The slates are plainly conformable with the green tuffs.

The black slates and green bedded tuffs are best developed along the north shore of Tongass Narrows from Ketchikan to Mountain Point. The black slates are in places considerably metamorphosed and schistose and might more correctly be called phyllites. They are closely interbedded with and grade into fissile green tuffs, both of which are interbedded with more massive tuffs. The green tuffs are also schistose and in places completely recrystallized. The greater part of the town of Ketchikan stands on rocks of this character, and excavations for street building show both the blocky and fissile types. The most schistose types are completely recrystallized and consist of secondary quartz, feldspar, calcite, epidote, and chloritic material. The massive types consist essentially of secondary epidote, hornblende, chlorite, sericite, and calcite, with pyroxene and plagioclase feldspar crystals almost entirely replaced by secondary minerals.

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[1] Martin, G. C., Triassic rocks of Alaska: Geol. Soc. America Bull., vol. 27, p. 700, 1916.

The schistose green tuffs referred to by Brooks[1] as greenstone schist and by Smith[2] as the green schist near Ketchikan, were regarded by both as Paleozoic. According to the present interpretation of the structure of Gravina and Revillagigedo islands these tuffs stratigraphically overlie the massive igneous rocks carrying Jurassic fossils and occupy a position near the top of the formation. Their schistose nature is believed to be due to contact metamorphism induced by the intrusive masses of Revillagigedo Island, as indicated by the increase of schistosity toward the igneous rocks on the northeast.

The base of the greenstone and slate series is evidently the coarse breccia found along the west coast of Gravina Island. It overlies the Upper Triassic sediments with apparent conformity. As previously brought out, the breccia grades upward into a more dominantly sedimentary series of green tuffs and black slates which are unconformably overlain by conglomerate, slate, and graywacke of Upper Jurassic or lower Cretaceous age.

STRUCTURE.

On Gravina Island the volcanic rocks of Dall Ridge occupy the trough of an overturned syncline, and the other two areas—one extending from Vallenar Point to Bostwick Inlet and the other on Tongass Narrows—form the two limbs of another overturned syncline, the trough of which contains the Upper Jurassic or Lower Cretaceous sedimentary rocks of Blank Inlet. The volcanic rocks on the northeast shore of Tongass Narrows are also believed to be overturned and to overlie stratigraphically the phyllites of Ward Cove and George Arm and the Carboniferous schist to the northwest, which seem to overlie the volcanic rocks.

ORIGIN.

The volcanic breccias at the base of the series are evidently the product of volcanic explosions. The perfect stratification of much of this igneous material and the conformable intercalations of slate and limestone show that at least portions of it were deposited or collected in water. The pillow-like structure of some of the flows that occur with the fragmental rocks indicates that they also were submarine.

AGE AND CORRELATION.

The age determination of the greenstone and slates rests upon rather slender paleontologic foundation. The collections from Bostwick Inlet were submitted to Mr. Stanton, who reports as follows:

9528 (15 ACh 104). Bostwick Inlet, Gravina Island.
9529 (15 ACh 105). Bostwick Inlet, Gravina Island.
Aucella sp.
Probably Upper Jurassic; possibly Lower Cretaceous.
9530 (15 ACh 106). Bostwick Inlet, Gravina Island.
Pecten? sp.
Not sufficient for determining age but probably from same formation as 9528 and 9529.

These fossils were collected from the west coast of Bostwick Inlet about half a mile south of the localities from which the Triassic and doubtful collections were made. The fossils occur in sedimentary beds apparently interbedded with the volcanic breccias and overlying the Triassic sediments, but the relations are somewhat obscured by the gravel covering.

Some correlations with rocks of known age are suggested. The greenstone and slate series extends more or less continuously along the mainland and adjacent islands of southeastern Alaska. In the Juneau region the recent detailed work of Spencer and Eakin shows a section similar to that exposed along Tongass Narrows and adjacent islands, and Brooks, who has studied both sections, believes that the black slate and greenstones of Ketchikan should be correlated with the andesitic flows and black slates of Juneau, which carry Triassic fossils. The finding of Upper Triassic fossils by Spencer and Eakin[3] in the slate and greenstone series of Juneau suggests to the writer the possibility that the rocks of Tongass Narrows are of similar age. Smith[4] notes the similarity between the volcanic rocks of Gravina Island and the augite melaphyres of the region north of Juneau, referred by Knopf[5] to the Upper Jurassic or Lower Cretaceous, and it is not at all unlikely that the upper portion of the slate and greenstone series of the Ketchikan district may be the equivalent of the volcanic rocks associated with the Berners formation. The slate and greenstone of the Ketchikan district may thus be correlated with both the Triassic and Jurassic rocks of the Juneau region.

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[1] Brooks, A. H., Preliminary report on the Ketchikan mining district, Alaska: U. S. Geol. Survey Prof. Paper 1, p. 48, 1902.

[2] Smith, P. S., op cit., p. 100.

[3] U. S. Geol. Survey Thirty-eighth Ann. Rept., p. 90, 1917.

[4] Smith, P. S., op. cit., p. 164.

[5] Knopf, Adolph, The Eagle River region, southeastern Alaska: U. S. Geol. Survey Bull. 502, p. 18, 1912.

Rocks of greater value for purposes of correlation occur on Vancouver and Queen Charlotte islands. The "Vancouver series," first defined by Dawson as Triassic, was later subdivided by Clapp[1] on the basis of distribution, lithology, and structure into the Nitinat formation, Vancouver volcanics, Sutton formation, Sicker series, and Metchosin volcanics. He uses the term "Vancouver group" in place of "Vancouver series" as used by Dawson. The Nitinat formation is made up of highly altered calcareous sediments and is regarded as Jurassic or Triassic (?). The Vancouver volcanics are composed largely of volcanic materials with interbedded sediments. On the evidence of fossils collected from the intercalated limestone beds of the Sutton formation the Vancouver volcanics are regarded by Clapp as lowermost Jurassic. The Jurassic age of these rocks, however, is not accepted by Martin,[2] who considers that the fossil evidence is not conclusive and that the Sutton limestone fauna may with equal confidence be called Upper Triassic. The Sicker series is made up of metamorphic, chiefly schistose sedimentary and volcanic rocks, with intrusive porphyrites. The stratigraphic relation of this "series" to the "Vancouver group" of which it forms a part is not certain, but it is believed to occur above the Vancouver volcanics.

On Graham Island, one of the Queen Charlotte group, the "Vancouver group" was subdivided by MacKenzie[3] into the Maude formation, referred to the Lower Jurassic and possibly in part to the Triassic, and the Yakoun formation, of Middle Jurassic age. The Maude formation is composed of a lower part, made up of banded slaty and flaggy argillites, in places carbonaceous, and an upper part of feldspathic sandstones. Partly crystalline bituminous massive limestones are provisionally classed with the Maude formation. Near the top of the formation, where it begins to grade into the overlying Yakoun formation, the sandstone contains igneous material. The Maude formation is regarded on fossil evidence as Upper Triassic and Lower Jurassic.

The conformably overlying Yakoun formation consists of water-laid agglomerates and tuffs, conglomerates, lavas, and possibly intrusives. Fossils contained in the intercalated sediments indicate a Jurassic age, suggesting correlation with the Tuxedni sandstone (Middle Jurassic).

The correlation of the lower part of the volcanic rocks of Gravina Island with the Vancouver volcanics and the upper part of the Maude formation is suggested. The upper part of the volcanic rocks of Gravina Island may be the equivalent, at least in part, of the Sicker series and the Yakoun formation. The age of the Gravina Island volcanic rocks is by no means certain. It is not at all unlikely that they contain both Triassic and Jurassic rocks and possibly some infolded Paleozoic rocks also.

UPPER JURASSIC OR LOWER CRETACEOUS ROCKS.

DISTRIBUTION AND CHARACTER.

A formation consisting essentially of interbedded conglomerate, graywacke, and black slate exposed along a wedge-shaped strip extending from Blank Inlet to the northeast coast of Gravina Island (see Pl. VIII, *B* and *C*) is determined on fossil evidence to be Upper Jurassic or Lower Cretaceous, and similar rocks just northwest of Ward Cove are correlated with this formation.

The conglomerate does not appear to be the basal member but occurs at intervals throughout the formation interbedded with the graywacke and slate. It is composed of rather fine grained pebbles with a few boulders as much as a foot in diameter. The matrix is essentially a graywacke but contains a considerable amount of igneous rock fragments. The pebbles and cobbles are mostly igneous and resemble the volcanic rocks of Gravina Island. Pebbles of dioritic rocks resembling the plutonic rocks of the Coast Range also occur. No members of this formation are known to be of igneous origin, although both matrix and cobbles of some of the conglomerates contain so great an amount of igneous material that they resemble agglomerates.

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[1] Clapp, C. H., op cit., p. 37.

[2] Martin, G. C., op. cit., p. 709.

[3] MacKenzie, J. D., Geology of Graham Island, B. C.: Canada Geol. Survey Mem. 88, p. 39, 1916.

The conglomerate passes by increasing fineness and decrease of igneous material into typical-looking graywacke with angular slate fragments. Microscopic examination of the graywacke shows it to consist essentially of quartz and feldspar grains with angular fragments of slate and decomposed particles of dioritic rocks, hornblende, pyroxene, and epidote. Flakes of biotite may be secondary, but no marked schistosity has developed.

The slates are very fissile black clay slates and are closely interbedded with the graywacke members. The slates have a marked cleavage. (See Pl. VIII, *C.*)

STRATIGRAPHIC RELATIONS.

These Upper Jurassic or Lower Cretaceous beds overlie the volcanic rocks of Gravina Island described above and regarded as Triassic or Jurassic, but in most places the relations are rather obscure. On the northeast shore of Bostwick Inlet near the entrance the slates and graywacke overlie the eroded surface of the volcanic rocks with marked unconformity. On the northeast shore of Gravina Island conglomerates and graywacke overlie the volcanic rocks without apparent angular unconformity. The conglomerate and graywacke of Ward Cove are noticeably unconformable upon the black phyllite that has been correlated with the Upper Triassic rocks.

STRUCTURE.

The conglomerate, slate, and graywacke beds of Blank Inlet occupy the trough of an overturned syncline in which are also involved the volcanic rocks of Gravina Island, which actually overlie them on the east shore of Blank Inlet.

ORIGIN.

These Upper Jurassic or Lower Cretaceous conglomerates, graywackes, and slates are the products of normal deposition in a shallow sea. The constantly changing character of the deposits indicates corresponding changes of conditions during their deposition. The materials of the rocks were apparently derived in part from the volcanic rocks of Gravina Island near by and in part from the surrounding regions.

AGE AND CORRELATION.

The age determination of the slates and graywackes of Blank Inlet rests on a single fossil collection from which only one form was identified. Mr. Stanton reports:

9527 (15 ACh 99). Blank Inlet, 1½ miles north of Blank Point, Gravina Island.
Belemnites sp.
Jurassic or Lower Cretaceous.

Smith[1] correlated the conglomerates and other sediments on the west coast of Gravina Island with these somewhat similar ones on Blank Inlet. However, besides the fossil evidence which now shows that the two are distinct, there are very marked differences in the lithology. The conglomerates of Threemile Cove are composed essentially of a peculiar type of igneous rock that was not noted on Blank Inlet, where the conglomerates contain a great amount of greenstones and dioritic rocks similar to the intrusives of the Coast Range, types neither of which was observed in the conglomerate of the west coast. The sedimentary beds of both Bostwick Inlet and the west coast contain beds of siliceous sandstone and quartzite but no appreciable amount of graywacke. On Blank Inlet the reverse is true; the arenaceous beds are dominantly graywacke, and pure quartzose beds are lacking. Structural differences are also very apparent. The conglomerate of Blank Inlet is considerably sheared; the rocks of the west coast are massive. This might appear to indicate a greater age for the rocks of Blank Inlet but the greater amount of deformation is no doubt due to the difference in composition of the rocks, the soft agglomeratic material being much more easily affected than the granite. It is a noticeable fact that the few diorite boulders in the conglomerate of Blank Inlet have withstood the deformation.

The rocks of the Queen Charlotte series, with which these beds of conglomerate, slate, and graywacke on Gravina Island were at first correlated, are now determined as Upper Cretaceous[2] and are thus younger than any known rocks of Gravina Island. The conglomerate, slate, and graywacke of Blank Inlet are possibly the equivalent of the Berners formation of Eagle River, the conglomerate, graywacke, and slate of Admiralty Island and other places in southeastern Alaska, and the Valdez group of Prince William Sound.

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[1] Smith, P. S., op. cit., p. 104.

[2] MacKenzie, J. D., op. cit., p. 65.

TERTIARY ROCKS.

The only rocks of Tertiary age within the area consist of rhyolite, which occurs on the peaks of Dall Head and extends from Thompson Cove nearly to Seal Cove. It is a light-gray dense rock composed essentially of quartz and feldspar. It overlies unconformably the granite and greenstones of Dall Head and has not shared in the mineralization of the underlying rocks. It was regarded by the Wrights and Smith as Tertiary.

QUATERNARY ROCKS.

GLACIAL DEPOSITS.

DISTRIBUTION AND CHARACTER.

The most recent sediments are the glacial deposits. Rocks of this character are not abundant but have been found at one place on Gravina Island. About half a mile northwest of the cabin at the head of Dall Bay is a small exposure of glacial material about 80 feet above sea level. The outcrop is concealed on all sides by vegetation. The exposed base contains about 2 feet of glacial till and blue clay and is overlain by stratified beds of glacial gravel about 5 or 6 feet thick. Fossils occur in both the blue clay and the stratified gravel.

AGE AND CORRELATION.

A small collection of fossils from the glacial deposits was submitted to W. H. Dall, who reports:

> I have examined the material from Dall Bay, Gravina Island. The material is a "boulder clay" which disintegrates in water, and when it is strained off the fossils remain in a clean condition. Near the Treadwell mine opposite Juneau the same formation extends to an altitude of 200 feet. The species contained in Mr. Chapin's collection are as follows:
>
> Cylichnella n. sp.
> Bela violacea Mighels.
> Colus sp., fragment.
> Cardium (Cerastoderma) ciliatum Fabricius.
> Axinopsis viridis Dall.
> Macoma calcarea Gmelin.
> Saxicava arctica Linné.
> Mya intermedia Dall.
> Balanus sp., fragment.
>
> The assembly naturally indicates the colder climate associated with the period of glaciation.

These fossiliferous deposits occur about 80 feet above high tide, a position that indicates an uplift of the land since the glacial epoch. Corroborative proof of a recent uplift is found in the elevated wave-cut benches found in this vicinity. That part of Gravina Island south of Dall Head, the bold promontory that marks the south end of the highlands of the island, is a flat plain (Pl. VIII, *A*). This and similar features on Annette Island and at other places near by are regarded as wave-cut benches. Smaller features of the same character are low-lying, flat benches along the coast, some a few feet above high tide and others only partly above water. The higher benches are forested and dissected by erosion, but others near the water level are bare of vegetation and apparently have been only recently uplifted, and it is not at all unlikely that this emergence has continued to the present time. As the benches are developed only locally, however, it is probable that the uplift was of a differential character and that some parts of the region are sinking below sea level and others are rising, owing to the warping nature of the movement.

MARINE GRAVELS.

During the period in which the fossiliferous deposits of Dall Bay stood at sea level the low depression that connects Vallenar Bay and Bostwick Inlet was evidently in large part flooded if not wholly covered. It is thus safe to assume that the gravels that mantle the floor of this "through" valley are largely marine, although partly reworked by later stream action. The valley floor is covered by vegetation which hides the deposits.

INTRUSIVE ROCKS.

The intrusive rocks of Dall Head were not examined in detail by the writer. On the west coast of Gravina Island they are apparently dioritic in composition and along the contact with the sediments are gneissoid. This structure is regarded as purely cataclastic; the gneissoid effect is commonly noted in the diorites at other places in the Ketchikan district and is not regarded as evidence of an older gneiss. On the extreme southern point of Gravina Island, however, Smith noted gneisses which he regards as Paleozoic, intruded by igneous rocks. He states:[1]

> At this place they consist of highly metamorphic gneisses and amphibolites which have been intruded by igneous rocks. Undoubtedly the older rocks have been metamorphosed locally by the younger intrusives, but apparently

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[1] Smith, P. S., op. cit., p. 97.

they were considerably metamorphosed dynamically before they were intruded. No definite determination of the age of the gneisses and amphibolites has been made. Judged by their physical character they seem to be much older than any of the known late Paleozoic rocks. Although their aspect may be due in large measure to the contact effects produced in proximity to the large intrusive masses, the impression gained in the field, and not dispelled by later investigations in the office, is that those rocks are probably at least as old as the middle or earlier part of the Paleozoic era.

The relation of the old gneisses and amphibolites to the other sedimentary rocks of the region is indefinite, because they occupy only a small area at the extreme end of the island and are surrounded on all sides by sea or by a large area of younger igneous rock. No other rocks on Gravina Island are correlated with these rocks near Dall Head.

The great abundance of coarse angular blocks of granite occurring in the Upper Triassic conglomerate suggests a near-by land mass of this rock. The gneisses noted above may be a remnant of this old land mass, but if so the granite must be locally metamorphosed, for the cobbles of the conglomerate are massive and have suffered little metamorphism. As previously stated, the material of the conglomerate is lithologically similar to the granite of Annette Island and is supposedly from a stock of similar composition.

The intrusives of Dall Bay and Seal Cove are granites and associated pegmatites or alaskites. These are composed essentially of quartz and orthoclase with a subordinate amount of muscovite and secondary sericite. They range in texture from medium-grained holocrystalline rocks to fine-grained aphanitic and porphyritic phases. They are evidently the equivalent of similar rocks occurring at several places on Prince of Wales Island and other localities. Wherever the relations were observed the granite has been found to be later than the quartz diorite and associated intrusives of the Coast Range, and is probably Cretaceous. The granite and quartz diorite of Gravina Island have not been separated on the map.

The intrusive rocks of Revillagigedo Island are quartz diorites and associated types and are to be correlated with the intrusives of the Coast Range. They occur as batholithic masses cutting diagonally across the sedimentary formations. They are regarded as Middle or Upper Jurassic, as the conglomerates of Upper Jurassic or Cretaceous age contain many boulders of similar rock, which is lacking in the earlier conglomerates.

TWO LAMPROPHYRE DIKES NEAR SANTAQUIN AND MOUNT NEBO, UTAH.

By G. F. Loughlin.

INTRODUCTION.

No description of lamprophyre dikes in Utah has heretofore been published,[1] and this paper is presented as an addition to the petrology of the State. The two dikes here described are on the west slope of the Wasatch Mountains, near Santaquin and Mount Nebo, and were noted by the writer in 1912, while he was engaged in a reconnaissance of the ore deposits of central Utah.

LOCAL GEOLOGY.

STRATIGRAPHY.

The steep western front of the Wasatch Mountains in the Santaquin and Mount Nebo region exposes rocks of pre-Cambrian, Paleozoic, and Tertiary age, whose relations are complicated by overthrust and block faulting.[2] (See fig. 13.)

The pre-Cambrian is represented by reddish gneissoid granite with pegmatite veins and included bodies of schist, exposed for 2 miles or more along the lower west slope of the main range southeast of Santaquin. This granite is overlain unconformably by Cambrian quartzite, dipping 28° E., which does not appear to be over 800 feet thick (aneroid measurement). The quartzite is prominent along the middle west slope east of Santaquin and about 5 miles northeast of Mona. It passes upward into Cambrian shale, which corresponds to the Ophir formation to the north and west, and this is followed by a great thickness of limestones, the lower beds of which are probably of Cambrian age and the higher beds certainly of Mississippian age. The upper Mississippian includes thin quartzite beds intercalated with limestone and shale. The limestones form the greater part of the range throughout the region, occupying most of the summit areas and upper western slopes and extending down to the west base of the range in the Mount Nebo mining district northeast of Mona.

The Tertiary rocks include coarse reddish conglomerate and concretionary limestone, which rest unconformably upon the Mississippian. They veneer the low ridges south and southwest of Santaquin and are very extensive on the east slope of the main range. These rocks are overlain by a coarse latite or andesite breccia, most of whose outcrops have been reduced to aggregates of loose cobbles.

DIKE ROCKS.

The only intrusive rocks noted in the region are the lamprophyre dikes that form the subject of this paper. The northern dike is southeast of Santaquin, on the Black Balsam claim. It cuts pre-Cambrian granite, is 3 feet thick, trends northeastward, and dips about 70° SE. It is closely paralleled for part of its course by a vein of calcite and fluorite which contains a little chalcopyrite, galena, and corresponding oxidation minerals. The southern dike is south of the mouth of Bear Canyon, northeast of Mona, on the property worked by the Eureka Leasing & Mining Co. in 1912. It cuts Mississippian limestone, is 4 feet wide, strikes N. 45°-50° E., and has a vertical dip.

There is no local evidence by which these dikes can be correlated with other igneous rocks. From their petrographic character, however, and their lack of deformation, it is assumed that they represent a late stage of the Tertiary volcanic period, which is well represented by latites or andesites on Long Ridge, west of Mona; by rhyolites, latites, and monzonite farther west, in the Tintic district,[1] and by granodiorite and quartz diorite to the north in the Cottonwood-American Fork region.[2] Lamprophyre dikes in the last-named region, according to Butler, are the latest of the intrusive rocks.

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[1] B. S. Butler has informed the writer that he has noted several biotite lamprophyre dikes during his recent detailed studies of the Cottonwood and Park City area in Utah.

[2] Loughlin, G. F., Reconnaissance in the southern Wasatch Mountains, Utah: Jour. Geology, vol. 21, pp. 447-451, 1913.

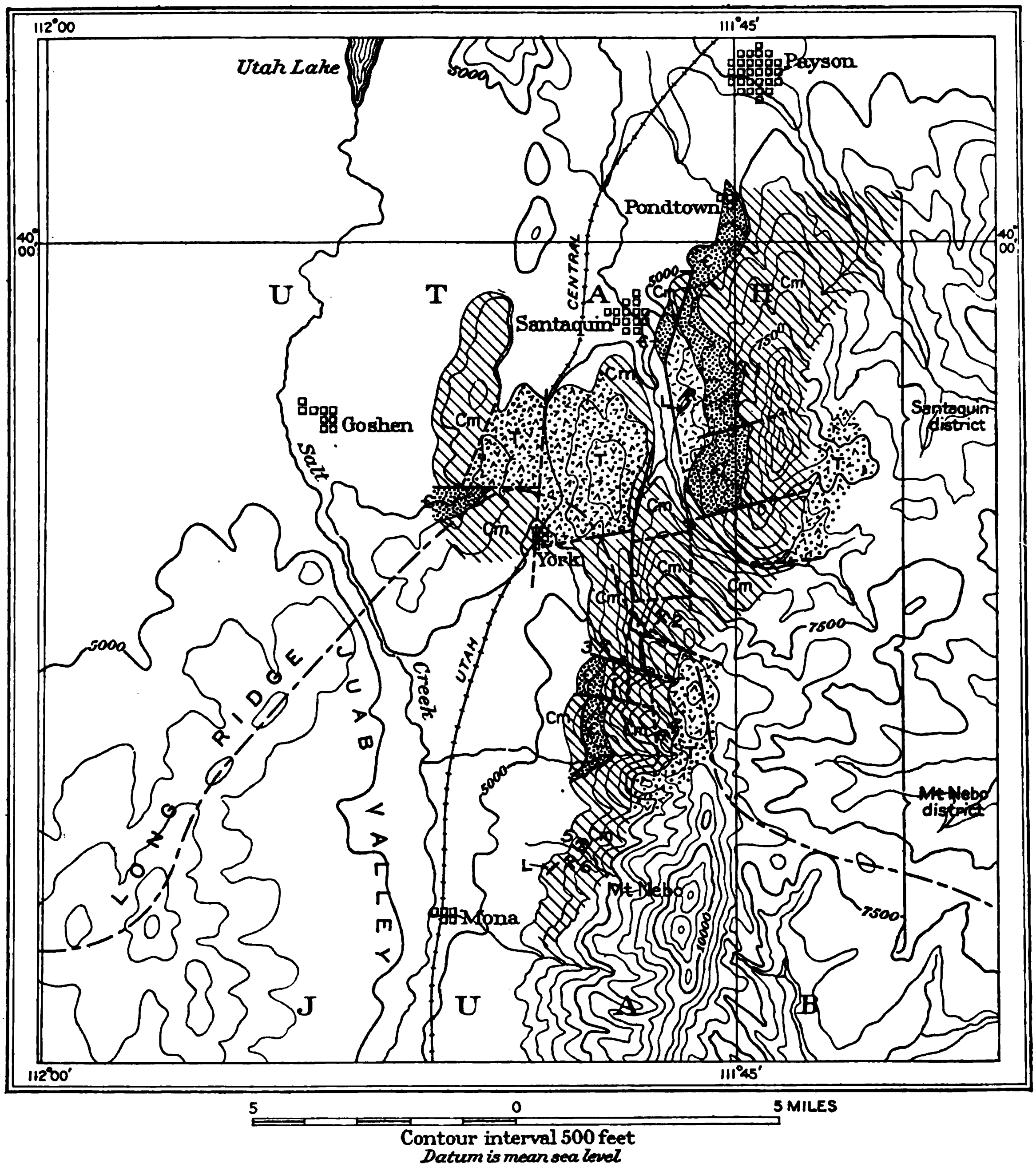

FIGURE 13.—Geologic map of the Santaquin and Mount Nebo region, Utah. Æ, pre-Cambrian granite; Є, Cambrian quartzite; Cm, Mississippian and earlier limestones; T, Tertiary conglomerate and volcanic rocks; L, lamprophyre dikes. List of mines: 1, Union Chief; 2, Santaquin Chief and Santaquin King; 3, Big Nebo; 4, Eva and Nebo Highland; 5, Spider; 6, Freddie Lode (Eureka Leasing Co.).

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[1] Lindgren, Waldemar, and Loughlin, G. F., Geology and ore deposits of the Tintic mining district, Utah: U. S. Geol. Survey Prof. Paper 107, pp. 42-75 (in press).

[2] Butler, B. S., and Loughlin, G. F., A reconnaissance of the Cottonwood-American Fork mining region, Utah: U. S. Geol. Survey Bull. 620, pp. 174-177, 1916.

STRUCTURE.

The attitude of the strata is for the most part homoclinal, with a prevailing dip of about 30° E., but some folds with steep to vertical dips are prominent east and northeast of Mona.

The most striking structural features of the region have been produced by overthrust and block faulting. The overthrusts are exposed, though not very clearly, east and south of Santaquin, near the north and south ends of the pre-Cambrian granite area; also along the west base of the range about 5 miles northeast of Mona. At all these places Mississippian limestone is overridden by Cambrian quartzite. The overthrust northeast of Mona clearly antedates the block faulting, as shown in figure 13. The relation of the overthrusts to local folding is not clear. They may be synchronous with or later than the folding, which elsewhere in Utah is assigned to post-Jurassic time but clearly antedates the intrusions of monzonite and related rocks with which ore deposits are genetically connected. The writer's investigations in the Cottonwood-American Fork [1] and West Tintic [2] districts, however, have proved that the overthrusts in those districts are older than the igneous intrusions and any accompanying deformations, which are probably of early Tertiary age, and he provisionally correlates the overthrusts in the Santaquin and Mount Nebo region with those in the districts mentioned.

The block faulting is marked by normal faults of northward and east-northeastward trends, most of which coincide in position with canyons. These faults were formed by the disturbances that caused the main uplift of the Wasatch Mountains and the ranges of the Great Basin. They are later than the volcanic breccia and presumably later than the two lamprophyre dikes and the ore deposits of the region, but there is no means of comparing the age of the dikes with any local faulting.

THE DIKES.

MEGASCOPIC CHARACTER.

The rocks are dark gray to black, dense, and porphyritic. Biotite is the only conspicuous megascopic mineral, forming irregular scales and tablets 3 millimeters or less in diameter. These phenocrysts constitute about 20 per cent of the rock and give it the characteristic luster of lamprophyre. Alteration products of olivine, consisting largely of calcite in small thinly scattered spots, are visible on close inspection of the dike near Santaquin. The application of dilute hydrochloric acid produces brisk effervescence in both rocks.

MICROSCOPIC CHARACTER.

NORTHERN DIKE.

The northern dike, as seen in thin section, consists of a prevailingly glassy groundmass crowded with phenocrysts of augite, biotite, olivine, and magnetite and minute crystals of apatite. Phenocrysts 0.5 to 1 millimeter in diameter constitute about 25 per cent of the rock. Feldspar is present only in the groundmass. The feldspar and glass form less than 50 per cent of the rock. Calcite, fibrous monoclinic amphibole, and chalcedonic quartz are alteration products.

Augite is the most abundant microscopic phenocryst, making up about 35 per cent of the rock. It forms typically twinned prismatic automorphic grains. The main part has an extinction angle ($\mathfrak{c} \wedge \dot{c}$) between 45° and 50°, whereas that of a narrow marginal zone is about 5° greater. These angles do not accord with Rosenbusch's statement [3] that the pyroxenes of lamprophyres are of the diopsidic variety, and this is one characteristic in which the two dikes are exceptional. The augite is very free from alteration.

Olivine in hypautomorphic crystals as much as 2 millimeters long originally formed about 3 per cent of the rock. These crystals are now mostly altered to aggregates of calcite and a finely fibrous to platy monoclinic amphibole. A few crystals are replaced by serpentine and calcite. No secondary magnetite accompanies the alteration products.

Biotite forms many irregular to automorphic brown grains and tablets, most of them less than 0.5 millimeter long but some more than 1 millimeter. The larger phenocrysts have borders that are darker brown than the main part, a common feature in the biotite of lamprophyres. All the biotite is of distinctly later growth than augite and olivine. As a whole it is free from alteration, but a few of the larger phenocrysts contain a little calcite.

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[1] Loughlin, G. F., op. cit., pp. 440-443. Butler, B. S., and Loughlin, G. F., A reconnaissance of the Cottonwood-American Fork mining region, Utah: U. S. Geol. Survey Bull. 620, pp. 178-179, 1916.

[2] Butler, B. S., and Loughlin, G. F., Ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111 (in press).

[3] Rosenbusch, H., Elemente der Gesteinslehre, p. 233, 1906.

Magnetite is present in fine grains, mostly of square outline, thickly scattered throughout the section. It is for the most part of later growth than the three minerals just described. No inclusions of it are found in the augite or olivine except along their margins, and very few are found in the biotite.

Apatite forms many small typical prisms. They appear to be mostly inclosed in biotite, but many in the groundmass may have been overlooked, owing to their close resemblance to the smallest augite crystals in transmitted light. No pyrite was identified in this section, although the chemical analysis signifies the presence of 0.24 per cent.

Feldspar is present in places, forming a poikilitic matrix for the minerals already described. It occurs in divergent or radiating aggregates, as shown by its extinction, but each aggregate appears to be a homogeneous crystal in other respects. Its mean index of refraction is a little above 1.52 and, together with the diverging habit, suggests albite. The isotropic groundmass has an index of refraction a little above 1.51. In a few places it forms small rounded areas free from phenocrysts and resembling an isotropic mineral such as analcite; but in some of these areas incipient growths of feldspar are recognizable, and no gelatinization was obtained by evaporation with hydrochloric acid. There is no sharp boundary between these rounded areas and the rest of the groundmass.

Chalcedonic quartz forms a few small irregular aggregates in the groundmass and is closely associated with calcite.

SOUTHERN DIKE.

The southern dike, as seen in thin section, consists of phenocrysts of biotite, augite, apatite, and magnetite in a groundmass of feldspar which has a distinctly diverging or radiating habit. Alteration products are pyrite, calcite, chalcedonic quartz, chlorite, and hematite.

In this rock biotite is more abundant than augite, constituting about 20 per cent of the section. It forms hypautomorphic crystals, the largest of which are not much over 1 millimeter in diameter. Its pleochroism, as a whole, is from medium brown to white. The borders of the crystals are darker brown than the main part. The central parts of some crystals are olive-colored. Alteration products, which are very scarce, include calcite and chlorite. The biotite crystallized later than the augite.

Augite forms hypautomorphic grains, none more than 1 millimeter long. The more prominent grains constitute about 5 per cent of the rock. Some grains show a little alteration to calcite, and some have fringes and veinlets of a very finely fibrous mineral, probably amphibole.

Apatite forms prominent though small typical prisms, the largest 0.2 millimeter long. Magnetite is present only as fine grains of square outline, some of which are altered to hematite.

The radiating feldspar which makes up the groundmass has a mean index of refraction a little above 1.52 and a large axial angle and is optically positive. These properties all indicate albite. No orthoclase was recognized. Little or no isotropic material is present in the groundmass.

Pyrite forms a few irregular grains as much as 0.3 millimeter in diameter, which may be impregnations of the groundmass rather than primary crystals.

Calcite, besides impregnating augite and biotite, forms a few small round to irregular aggregates impregnating the groundmass. Some of these are accompanied by chalcedonic quartz and some by pyrite.

CHEMICAL COMPOSITION.

The chemical composition of the northern (Santaquin) dike is shown by the analysis in column 1 of the accompanying table, which includes also the most closely corresponding analyses given by Washington.[1]

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[1] Washington, H. S., Chemical analyses of igneous rocks: U. S. Geol. Survey Prof. Paper 14, pp. 315-317, 1903. A second edition (Prof. Paper 99) of this work has been issued since the completion of the present paper.

Chemical analyses of lamprophyre from Santaquin, Utah, and rocks of similar composition.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	45.59	45.47	46.67	48.36	51.68	48.73	52.09	48.66	44.27	46.47	49.45	50.79
Al_2O_3	12.02	13.07	12.64	12.42	14.07	11.92	11.93	12.36	10.73	15.97	14.41	15.26
Fe_2O_3	3.84	6.72	6.13	5.25	4.71	4.79	1.84	3.08	3.63	5.97	3.39	3.29
FeO	5.05	12.43	10.17	2.48	4.57	4.56	7.11	5.86	5.87	4.27	5.01	5.54
MgO	7.09	2.80	5.64	9.36	7.72	5.93	12.48	8.09	13.05	5.87	8.26	6.33
CaO	10.21	6.79	11.48	8.65	6.65	9.24	7.84	9.97	10.80	10.54	6.73	5.73
Na_2O	1.82	2.04	1.64	1.46	2.45	2.62	2.04	2.71	1.07	1.69	2.54	3.12
K_2O	3.90	3.36	2.31	3.97	4.16	2.47	3.01	5.15	4.43	4.83	4.69	2.79
H_2O+	3.59	6.06	2.64	5.54	2.09	1.52	.35	1.46	3.23	2.32	2.43	2.74
H_2O-	1.64											
CO_2	1.91					5.80	.16				.61	2.97
TiO_2	1.67			1.18	1.08	1.34	.73	.97	1.37	1.33	1.23	1.02
ZrO_2	None.											
P_2O_5	1.33	.52	.74	.84	.72	.32	.34	1.07	.83	.73	1.12	.35
MnO	.16	.21	.19	.13	Trace.	.36	.15	.13	.06	.01	.13	.07
BaO	.20			.29		Trace.		.40	.48			
SrO	.16							.09	.18			
S	.13				.13	.34						
Cr_2O_3	Not det.	.28	.34	Trace.			.10					
NiO							.07					
Cl						.11						
Li_2O					Trace.	Trace.						
Sum	100.31	99.85	100.49	99.93	100.03	100.05	100.24	100.00	100.00	100.00	100.00	100.00
Specific gravity	[a]2.755	2.331	2.703				2.94					

[a] Apparent specific gravity. The apparent specific gravity of the southern (Mona) dike is 2.680.

1. Albite minette, Black Balsam claim, Santaquin, Utah. George Steiger, analyst.
2, 3. Basalt, Assab, near Massowa, Abyssinia. Ricciardi, L., Soc. geol. italiana Boll., vol. 5, p. 59, 1886.
4. Absarokite, Clarks Fork, Yellowstone National Park. Iddings, J. P., Jour. Geology, vol. 3, p. 938, 1895; U. S. Geol. Survey Mon. 32, pt. 2, p. 329, 1899.
5. Absarokite, Two Ocean Pass, Yellowstone National Park. Iddings, J. P., U. S. Geol. Survey Mon. 32, pt. 2, p. 329, 1899.
6. Kersantite, Big Horn Pass, Yellowstone National Park. Iddings, J. P., U. S. Geol. Survey Mon. 32, pt. 2, p. 70, 1899.
7. Kentallenite, Glen Shira, Argyllshire, Scotland. Hill, J. B., and Kynaston, H., Geol. Soc. London Quart. Jour., vol. 56, p. 537, 1900.
8. Average shonkinite. Daly, R. A., Am. Acad. Arts and Sci. Proc., vol. 45, p. 228, 1910.
9. Average missourite. Daly, R. A., op. cit., p. 229.
10. Average leucite basalt. Daly, R. A., op. cit., p. 229.
11. Average minette. Daly, R. A., op. cit., p. 233.
12. Average kersantite. Daly, R. A., op. cit., p. 233.

The noteworthy features of this analysis are low SiO_2 and relatively high alkalies, with K_2O in excess of Na_2O, which class the rock with alkaline varieties rather than normal basalt; also the high content of H_2O, CO_2, TiO_2, and P_2O_5. The H_2O+ is only in part accounted for by biotite and the fibrous amphibole to which olivine is altered, and the remainder is evidently present in the isotropic groundmass, partly in small bubble inclusions and partly in solid solution. CO_2 is present in calcite, which was introduced either at the close of consolidation or somewhat later, at the time of ore deposition. The TiO_2 is definitely referred to fine rutile needles in biotite and is doubtless present as a minor component of biotite, augite, and magnetite. The fact that the finely powdered rock is almost entirely picked up by a weak hand magnet is proof that little or no free ilmenite is present. The high P_2O_5 is attributable to abundant apatite, which is a characteristic feature of lamprophyres and certain other rocks of similar chemical composition.

Apparent discrepancies between the analysis and the mineral composition (mode) of the rock are the high CaO (about 6.5 per cent available for silicates), in contrast to the absence of calcic plagioclase, and the relatively high K_2O, in contrast to the absence of recognizable orthoclase. In the calculation of the mode, however, the CaO is found to be just sufficient very similar, as are his average analyses of missourite and leucite basalt.[1] The similarity of the minettes of the Highwood Mountains to the shonkinites of the same region was pointed out by Pirsson.[2] The relatively low content of water, especially H_2O+, in shonkinites may be attributed in part to its escape during relatively prolonged crystallization as well as to freedom from alteration.

CORRELATION AND GENESIS.

Minettes and kersantites are generally regarded as mafic products, complementary to aplites, of the differentiation of granitic and dioritic magmas and are found closely associated with large intrusive masses of these rocks. The nearest mass of post-Cambrian granite or granodiorite to Santaquin and Mona is about 35 miles to the north, in the Cottonwood and American Fork mining region,[3] and the only other intrusive mass within an equal distance is the monzonite stock of the Tintic mining district, 18 miles to the west.[4] The fact that the dike near Mona cuts Carboniferous limestone precludes correlation with the pre-Cambrian granite of the Santaquin district. Correlation of the dikes with certain intrusive stocks is therefore impossible. As the Cottonwood and Tintic stocks, above mentioned, were intruded in Tertiary time, and as the extensive sheets of lavas in central Utah were erupted in Tertiary time, it is inferred that the two dikes also are of Tertiary age.

The volcanic breccia in the Santaquin district is of latitic or andesitic character, as are the greater part of the volcanic rocks to the west as far as the Tintic district. The only rhyolites of the region are closely related to the monzonite and latite of the Tintic district in both occurrence and composition. It seems probable, therefore, that the two minettes under discussion are genetically related to a monzonitic magma represented by the latite breccias and flows of the region. The norm of the Santaquin dike (p. 106) is monzonitic as regards ratio of feldspar, though high in femic minerals.

The isolation of the Santaquin dike from other intrusive rocks prevents more than general speculation regarding its origin, which may be attributed, first, to a concentration of femic constituents and normative calcic plagioclase in a monzonite magma; second, to conditions that caused the crystallization of abundant biotite and aluminous augite instead of less aluminous mafic minerals and calcic plagioclase. It may be assumed, in accordance with Bowen's hypothesis,[5] that at some stage in the period of monzonitic intrusions and eruptions parts of the magma undergoing gravitative differentiation became enriched in alkalies, water, and other volatile constituents, which both increased fluidity and lowered the temperatures of crystallization. Further differentiation was thus promoted, and separation of the heavier constituents continued. These constituents may have been redissolved to some extent by sinking to a depth where the temperature was high enough, thus forming a basic submagma relatively high in alkalies and water. Whether or not this happened, final crystallization took place as follows: Olivine crystallized until the temperature became too low for it to exist in equilibrium with the magma; then, instead of hypersthene, diopside, and calcic plagioclase, the more complex mineral, augite, formed. Although augite contains very little water, the fact that it does not crystallize from dry fusions indicates that water and other volatile constituents of the magma may have been the factors that determined its crystallization. The zonal character of the augite, showing an increase in content of alumina as it grew, is of interest in view of the absence of the anorthite molecule in the feldspar of the rock. At still lower temperature biotite, a hydrous mineral that probably contains fluorine, crystallized, perhaps overlapping the period of later augite in the groundmass to some extent. After the larger biotite crystals had nearly attained their growth, magnetite crystals begin to form, but the magma solidified before they could attain any considerable size.

The position of apatite in the order of crystallization is not so definite as that of any of the other minerals, owing to the small size of its crystals. They are clearly older than the large biotite crystals but are not found inclosed in olivine or augite.

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[1] Daly, R. A., op. cit., pp. 228, 229.

[2] Pirsson, L. V., Petrography and geology of the igneous rocks of the Highwood Mountains, Mont.: U. S. Geol. Survey. Bull. 237, pp. 145-146, 1905.

[3] Butler, B. S., and Loughlin, G. F., A reconnaissance of the Cottonwood-American Fork mining region, Utah: U. S. Geol. Survey Bull. 620, pp. 175-176, 1916.

[4] Lindgren, Waldemar, and Loughlin, G. F., Geology and ore deposits of the Tintic mining district, Utah: U. S. Geol. Survey Prof. Paper 107, pp. 64-69 (in press).

[5] Bowen, N. L., The later stages of the evolution of the igneous rocks: Jour. Geology, supplement to vol. 23, No. 8, pp. 41-61, 1915.

Crystallization of feldspar, partial in the Santaquin dike and complete in the Mona dike, marked the final stage of consolidation. Considerable of the water and other volatile matter not entering into biotite was retained in the rock, either as minute fluidal inclusions or dissolved in the glass groundmass. The retention of water and other volatile matter may be an important factor in rendering lamprophyres especially subject to hydration and carbonatization. Olivine is evidently unstable in their presence, even at high temperatures. Other minerals or glass in equilibrium with them at high temperatures are subject to attack by them at low temperatures, and the long time since consolidation, supplemented by dynamic disturbances that caused fracturing, would favor hydration and carbonatization. The presence of metalliferous deposits in contact with or close by the Santaquin and Mona dikes leaves the source of water and carbon dioxide in their alteration products in doubt, but the suggestion may be worthy of consideration in the study of other lamprophyres.

RELATIONS OF LATE PALEOZOIC AND EARLY MESOZOIC FORMATIONS OF SOUTHWESTERN MONTANA AND ADJACENT PARTS OF WYOMING.

By D. Dale Condit.

SUMMARY OF CONCLUSIONS.

The object of this paper is twofold—to present evidence found in southwestern Montana concerning the great Jurassic base-leveling and its bearing on the solution of certain stratigraphic problems involving late Paleozoic, Triassic, and Jurassic formations, and to set forth the relations of those formations to beds in western Wyoming. The conclusions briefly summarized are as follows:

Prior to the encroachment of the sea from the northwest in late Jurassic time prolonged erosion and base-leveling occurred over much of the Rocky Mountain region. From the Idaho State line near Yellowstone National Park northward to the vicinity of Helena the erosion surface thus produced truncates beds of Triassic and Carboniferous age, through a stratigraphic range of about 1,000 feet.

The Quadrant quartzite at the type locality in the northwestern part of Yellowstone Park is approximately equivalent to the Amsden and Tensleep formations in Wyoming. The Park City (Pennsylvanian and Permian), Dinwoody (Lower Triassic), and Chugwater (largely Triassic) of the Wyoming section are in part represented by the Teton formation of Yellowstone Park. The quartzitic cherty basal beds of the Teton, containing the phosphate rock, are equivalent to the Phosphoria formation of Idaho, which corresponds to the upper part of the Park City formation. In western Montana north of latitude 45° 30′ the overlying Triassic shaly limestone and red shale were removed by the Jurassic erosion and the Ellis formation (Upper Jurassic) rests on the partly eroded Phosphoria formation.

FIELD WORK.

The information set forth in this paper was obtained by the writer during the seasons of 1913, 1915, and 1916. The first two years were spent in detailed mapping of the Permian phosphate beds along the northeast slope of the Wind River Mountains and throughout the Owl Creek Mountains of Wyoming. A reconnaissance trip was also made on both the east and west slopes of the Big Horn Mountains. In 1916 a reconnaissance examination occupying about three months was made in Montana from Helena south to Yellowstone Park and west to longitude 112°, and later in the same season a visit was made to exposures in the vicinity of Cody, Wyo. Nearly all the outcrops in Wyoming represented on the accompanying map (Pl. IX) except those near the Idaho State line were visited, and also practically all those in the Montana area.

FORMATIONS IN SOUTHWESTERN MONTANA DISCUSSED IN THIS PAPER.

The Madison limestone, of Mississippian age, which ranges in thickness from 200 to 2,500 feet in different parts of Montana, Idaho, and Wyoming, forms an unmistakable unit throughout the region and a convenient datum in the study of the less constant higher beds. Its slightly uneven surface is in places capped by conglomerate made up of pebbles of the Madison limestone in a sandy matrix. No generalized section of beds above the Madison that is representative of all of southwestern Montana can be made, and therefore each formation will be described briefly in turn and illustrated by stratigraphic sections measured at a number of localities.

QUADRANT QUARTZITE.

The term Quadrant was introduced by Peale[1] to designate a formation consisting of 150 feet of cherty limestones in the upper part and 200 feet of red limestones below, overlying the Madison limestone in the vicinity of Three Forks, Mont. The names for the Paleozoic formations in the Three Forks area were stated by Peale[1] to have been determined "after consultation with the members of Mr. Arnold Hague's division." The strata to which the name Quadrant was applied were therefore doubtless correlated with the strata, mostly quartzitic sandstone, found on Quadrant Mountain, in the northwestern part of Yellowstone Park, for which Arnold Hague and W. H. Weed, who surveyed the park between the years 1883 and 1893, had selected the name Quadrant quartzite. The publication of the Yellowstone Park folio, with four geologic maps, was delayed until 1896. In 1894, however, the name Quadrant quartzite was again used, by Weed,[2] for the rocks overlying the Madison limestone and underlying the Ellis formation in the Livingston quadrangle, Mont., which doubtless were regarded as equivalent to the typical Quadrant quartzite of the Yellowstone Park. Since 1896 the name has been extensively used for strata in many parts of western Montana supposed to be equivalent to those at the type locality.

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[1] Peale, A. C., U. S. Geol. Survey Bull. 110, pp. 39-43, pls. 1, 4, 1893.

Peale did not give any description of the formation at the type locality, and the first published section of the rocks of Quadrant Mountain is that measured by Weed[3] and quoted on page 117 of this report. It will be noted that the overlying cherty quartzitic beds described as the Phosphoria (Permian) in this paper are included by Weed in the Teton formation. Although the Teton beds of the Yellowstone Park region are also present in the south third of the Three Forks quadrangle, they were mapped as a part of the Ellis (Jurassic) in the Three Forks folio, except that the lower cherty quartzitic portion (Phosphoria) was considered a part of the underlying Quadrant. The reference of the lower part of the Teton to the Quadrant has been followed in all the geologic folios published for areas in western Montana, including the Philipsburg.[4] Pardee,[5] however, in a recent report on the Philipsburg region, defines the limits of the Quadrant (?) and Phosphoria formations as applied in that area.

There has been considerable uncertainty concerning the age of the Quadrant quartzite. Peale's studies in the Three Forks quadrangle yielded fossils of Mississippian and Pennsylvanian age. Collections of fossils made years ago by Weed and others northeast of the Three Forks area were found to contain Mississippian forms, and more recent collections northwest of the Three Forks area, within and near the Philipsburg quadrangle, have yielded Pennsylvanian forms. Field work in 1916 showed that the typical Quadrant in the Yellowstone Park, as described by Weed in Monograph 32, included representatives of both the upper Mississippian and the Pennsylvanian.

The Quadrant generally consists of three parts. The basal member is chiefly sandy red shale, slightly calcareous, containing few recognizable marine fossils. This red-shale member is only a few feet thick along the Idaho State line but thickens northward to about 150 feet near Bozeman. Over the red shale is more or less limestone and carbonaceous shale, absent locally but present in widely separated localities and containing abundant fossils, which are believed by G. H. Girty probably to denote early Pennsylvanian age. At the west boundary of Yellowstone Park this limestone is less than 50 feet thick and sparingly fossiliferous, but it thickens westward to 250 feet in the Snowcrest Range, where it is rich in fossils. At Lombard, about 75 miles northeast of the Snowcrest Range, it is nearly as prominent and equally fossiliferous, but at intervening points it is generally thin and contains poorly preserved fossils. The limestone member is overlain by 100 to 400 feet of quartzitic sandstone interbedded with a less amount of sandy dolomitic limestone and thin layers of smooth-textured argillaceous limestone, more or less cherty and containing traces of poorly preserved fossils.

The thickness of the Quadrant is in most places a little more than 300 feet, but from the Gravelly Mountains west to the Snowcrest Mountains the thickness increases from about 500 to nearly 1,000 feet. The formation also thickens northeastward from Lombard, a point on Missouri River about 35 miles northwest of Bozeman.

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[1] Idem, p. 14.

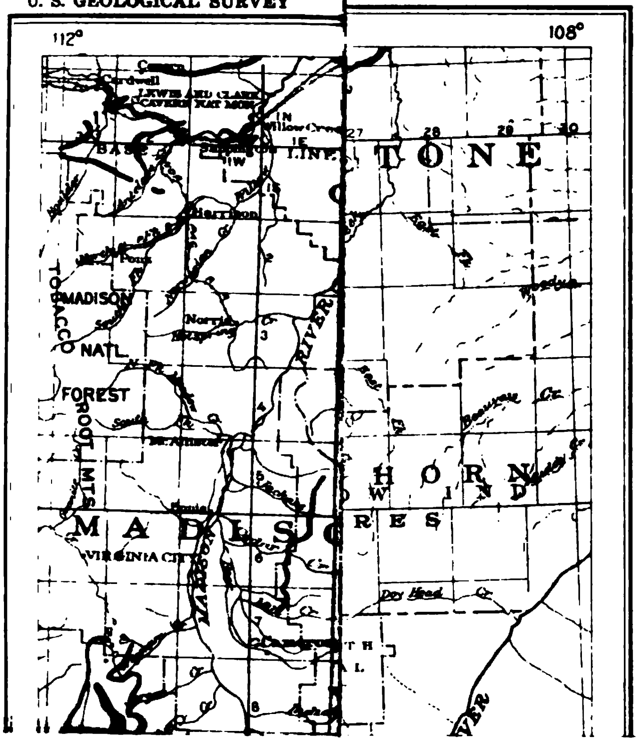
[2] Weed, W. H., U. S. Geol. Survey Geol. Atlas, Livingston folio (No. 1), 1894.

[3] U. S. Geol. Survey Mon. 32, pt. 2, p. 34, 1899.

[4] U. S. Geol. Survey Geol. Atlas, Philipsburg folio (No. 196), 1915.

[5] Pardee, J. T., The Garrison and Philipsburg phosphate fields, Mont.: U. S. Geol. Survey Bull. 640, pp. 206-211, 1917.

U. S. GEOLOGICAL SURVEY AL PAPER 120 PLATE IX



PHOSPHORIA FORMATION.

The Quadrant proper is overlain by 100 to 250 feet of dark-gray cherty quartzite, layers and ropy masses of nodular chert and shale, with one or more beds of phosphate rock. The sequence is regarded as equivalent to part of the Park City formation of Utah and Wyoming, but more nearly equivalent to the Phosphoria formation of Idaho, as was recognized in 1913 by Richards[1] and later by Stone and Bonine,[2] in whose report the name was first published for those beds in Montana. Peale,[3] in mapping the geology of the Three Forks quadrangle, included the Phosphoria beds as a part of the Quadrant, and he has been followed by Calkins[4] in mapping the Philipsburg quadrangle. Weed and others,[5] however, included these beds in the Teton formation of the Yellowstone Park region, which comprises beds ranging in age from late Pennsylvanian to Triassic, and forming three dissimilar lithologic units. The grouping is somewhat similar to that of the Embar formation of Wyoming, which includes Pennsylvanian and Permian limestone and Triassic shale.

The plane of contact between the Phosphoria and Quadrant proper is not easily drawn in all places, for the reason that there is no marked change in the lithology of the beds. The line of division is commonly marked by a few inches of conglomerate and a nonpersistent bed of phosphate rock, apparently of clastic origin. It is suspected that these beds denote an unconformity. The overlying rock is dark-gray cherty quartzite with scattered phosphorite granules, differing chiefly in color from the purer quartzitic sandstone below, which is pinkish gray, cross-bedded, and intercalated with argillaceous creamy limestone.

The Phosphoria is notably siliceous, being either cherty or quartzitic almost throughout. In Yellowstone Park and to the west along and near the Idaho State line the irregular layer of phosphate rock at the base is made up of fragments of phosphatized shells of the brachiopod *Lingulidiscina utahensis*, together with fossil bones. In some places the phosphatic material appears as a resinous brown substance, forming a cement for the quartz sandstone. At 30 to 60 feet above the base of the Phosphoria occur other phosphatic beds consisting of one or more layers of gray to black oolitic phosphorite and perhaps a few feet of dark shale overlain by chert either in thin wavy layers or as nodular masses mixed in an irregular manner with brownish quartzitic sandstone. At irregular intervals in the sandstone there are peculiar distorted cylindrical columns of lighter-colored sandstone 1 to 4 inches in diameter, perpendicular, or nearly so, to the bedding planes. Both the shale and the phosphate beds are lacking a short distance northeast of a line drawn from Helena to the northwest corner of Yellowstone Park. The uppermost beds of the Phosphoria contain poorly preserved brachiopod shells and fish bones, probably of Permian age.

TETON FORMATION.

The Teton formation, as defined by Weed for Yellowstone Park, included the rocks now named Phosphoria formation, and the overlying Triassic brown shaly limestone and red sandy shale. The brown limestone is unmistakably related to the Dinwoody formation of western Wyoming. This relation was suspected by Blackwelder,[6] who states that the lower part of the Teton formation is probably equivalent to the Embar of Wyoming. The overlying red shale is in part equivalent to the Chugwater formation of Wyoming and probably to the Thaynes limestone of Idaho. The part of the Teton beds overlying the Phosphoria is approximately 800 feet thick along the Idaho State line west of Yellowstone Park, but as shown by figure 14 this part was beveled by the Jurassic erosion and completely removed north of latitude 45° 30′, both west and east of Yellowstone Park.

Fossils of Triassic age are plentiful in the shaly brown limestone. No fossils were found in the red shales, but above them is locally a bed of richly fossiliferous limestone which at one point along the Idaho State line south of Red Rock Lakes was found to contain a pleurotomarioid gastropod, possibly identical with or closely resembling one that occurs in the Thaynes limestone in southeastern Idaho. The paleontologic and lithologic evidence at hand does not warrant positive statements as to the relations of the upper part of the Teton to the Idaho or Wyoming sections. Exclusion from the Teton of the basal portion, equivalent to the Phosphoria formation, leaves the higher shaly brown limestone and red beds of Triassic age to which the name Teton could be applied, but this seems inadvisable for several reasons, one of which is that the name has not been used for areas outside of Yellowstone Park. It is therefore believed that the use of the name Teton will be discontinued when enough additional field work shall have been done both in Montana and southeastern Idaho to permit the proper application of formation names now in use in Idaho and Wyoming.

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[1] Richards, R. W., unpublished manuscript.

[2] Stone, R. W., and Bonine, C. A.,The Elliston phosphate field, Mont.: U. S. Geol. Survey Bull. 580, p. 375, 1914.

[3] Peale, A. C., U. S. Geol. Survey Geol. Atlas, Three Forks folio (No. 24), 1896.

[4] Calkins, F. C., and Emmons, W. H., U. S. Geol. Survey Geol. Atlas, Philipsburg folio (No. 196), 1915.

[5] Hague, Arnold, Iddings, J. P., Weed, W. H., Walcott, C. D., Girty, G. H., Stanton, T. W., and Knowlton, F. H., Geology of the Yellowstone National Park: U. S. Geol. Survey Mon. 32, pt. 2, 1899.

[6] Blackwelder, Eliot, A reconnaissance of the phosphate deposits in western Wyoming: U. S. Geol. Survey Bull. 470, p. 455, 1911.

ELLIS FORMATION.

In late Jurassic time, subsequent to a long erosion interval during which there was more or less tilting of the strata, a subsidence brought in from the northwest an arm of the sea in which were deposited the sediments of the Ellis formation. The rocks consist of fossiliferous greenish shale and limestone and a variable amount of rust-brown weathering sandstone and conglomerate. At Elkhorn mining camp, near Helena, and for 70 miles to the south, the Ellis beds rest on more or less disturbed strata of the Phosphoria formation, but farther south the Ellis and Phosphoria are separated by Triassic shaly beds that thicken southward and constitute a portion of the Teton formation. The Ellis beds are about 200 feet thick in Yellowstone Park but thicken northward and northwestward to about 400 feet in the Livingston and Philipsburg regions. It is suspected that the Ellis represents only the basal portion of the several thousand feet of the marine Jurassic beds in southeastern Idaho but corresponds closely with the Sundance formation of Wyoming.

KOOTENAI FORMATION.

Overlying the Ellis formation is a motley aggregation of beds consisting in great part of red and green shale with conglomeratic sandstone and quartzite, and including near the top a limestone member crowded with gastropods. These beds, which are wholly nonmarine, lie between the marine Jurassic and marine Upper Cretaceous beds. On the basis of lithology they are correlated with the Kootenai formation of the Philipsburg quadrangle, which is Lower Cretaceous. They

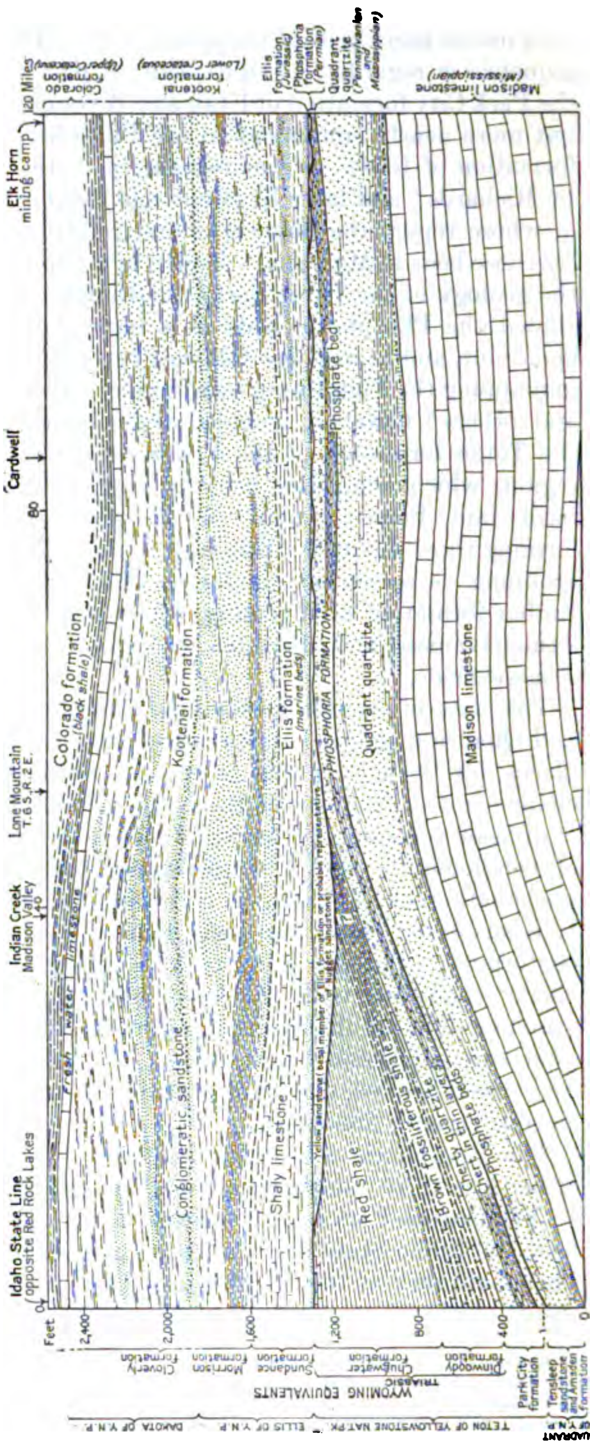
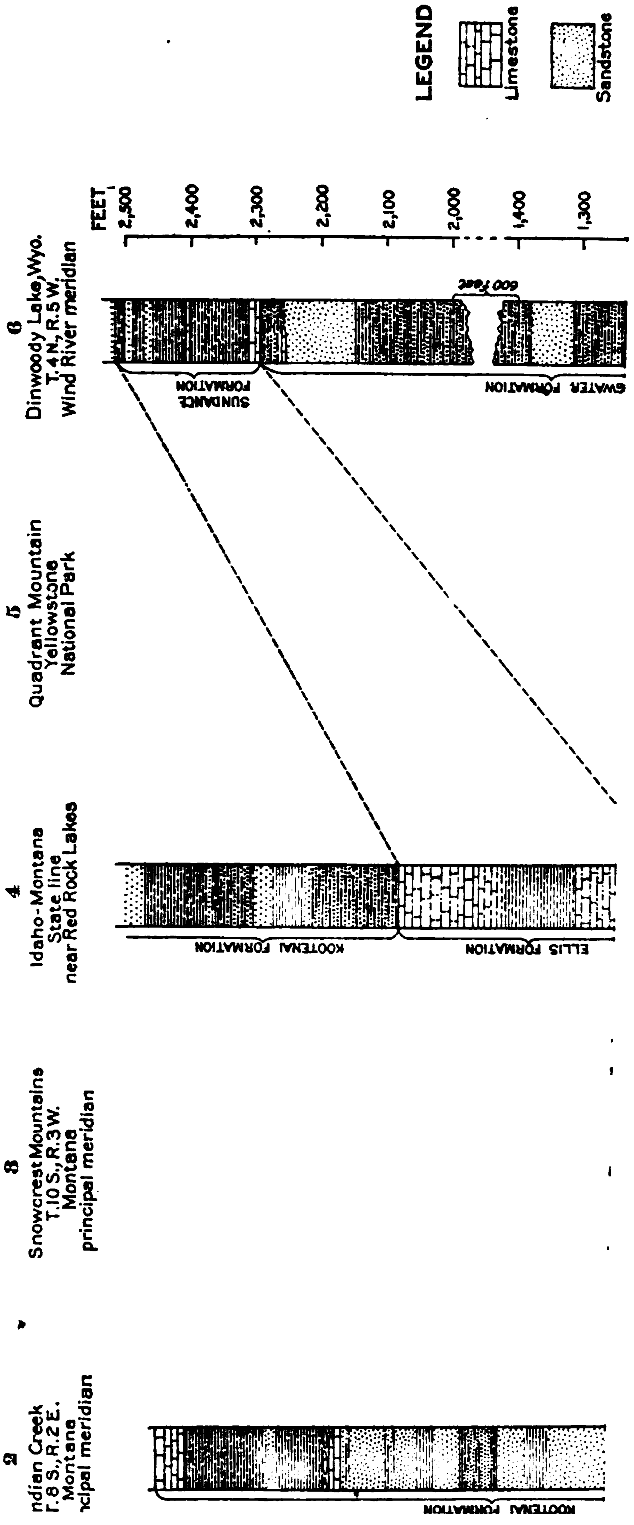

Colorado formation (Upper Cretaceous)
Kootenai formation (Lower Cretaceous)
Ellis formation (Jurassic)
Phosphoria formation (Permian)
Quadrant quartzite (Pennsylvanian and Mississippian?)
Madison limestone (Mississippian)
120 Miles
Elk Horn mining camp
Cardwell
80
Lone Mountain T. 6 S., R. 2 E.
Indian Creek Madison Valley
40
Idaho State Line (opposite Red Rock Lakes)
0
Colorado formation (black shale)
Fresh-water limestone
Kootenai formation
Conglomeratic sandstone
Ellis formation (marine beds)
Shaly limestone
PHOSPHORIA FORMATION
Phosphate bed
Red shale
Quadrant quartzite
Brown fossiliferous shale
Cherty quartzite
Chert in thin beds
Phosphate beds
Madison limestone
Feet
2,400
2,000
1,600
1,200
800
400
0
Cloverly formation
Morrison formation
Sundance formation
Chugwater formation
TRIASSIC
Dinwoody formation
Park City formation
Tensleep sandstone and Amsden formation
WYOMING EQUIVALENTS
DAKOTA OF Y. N. P.
ELLIS OF Y. N. P.
TETON OF YELLOWSTONE NAT. PK.
QUADRANT OF Y. N. P.

FIGURE 14.—Diagrammatic cross section from Idaho-Montana State line near Yellowstone National Park to the vicinity of Helena, Mont.



	Feet.
....	56
containing and sand-..........	4
sandstone, of Madison of Madison	80

ALLEY.

iver from the Cameron. Its ontaining nu- f the Madison d basin in the of the stream a sharp can- an rocks bor- ocks that dip 20 and 21, T. n wall (local- exposures of e to the top of nearly 2,000 lacement cuts his point but f the higher eds measured

mt.

	Ft.	in.
crowded	50	
y layers cy lime- acture..	400	
....	38	
....	64	
glomer- s mostly	32	
ers......	49	
dulating	158	
ers......	59	
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....	28	

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may possibly include the equivalent of the Morrison formation. The thickness of the Kootenai ranges from 1,000 to 1,500 feet.

The most conspicuous beds of the Kootenai are the gray gastropod limestone and a bed of conglomeratic sandstone in about the middle of the formation, the pebbles of which are dark chert. Both the beds are reported at many places in western Montana, in Yellowstone Park, and in the adjacent country in Wyoming. They form hogbacks projecting above the poorly exposed shaly red beds of the Kootenai and the dark shale of the overlying Colorado formation.

STRATIGRAPHIC DETAILS IN THE MONTANA AND YELLOWSTONE PARK AREA.

[See Pl. X.]

JEFFERSON RIVER CANYON NEAR CARDWELL.

A few miles east of Cardwell, which is on Jefferson River near the mouth of Boulder River, the broad valley narrows to a sharp canyon just wide enough for the tracks of the two railroad lines between the river and steep cliffs. On the south side of the valley (locality 1, Pl. IX) are complete exposures of the Quadrant and Phosphoria formations, dipping steeply northwestward. Several faults introduce some doubt as to the total thickness, but the sequence of the beds is clear. A condensed section of the beds measured here follows:

Section near Cardwell, Mont.

	Feet.
Ellis formation:	
Limestone, sandy, impure, cross-bedded; weathers to rust-brown color; lower beds contain fossils	36+
Phosphoria formation:	
Quartzite, dark gray, containing a few quartz pebbles and bands of chert and a layer of travel-rounded chert pebbles at top	42
Chert in thin shaly layers	6
Phosphatic beds consisting of phosphate rock, limestone, sandstone, shale, and chert, mostly in thin beds	35
Sandstone, dark gray, slightly dolomitic and cross-bedded, containing peculiar ropy masses and markings	29
Quadrant quartzite:	
Quartzite, alternating with dolomitic limestone and thin chert layers; poorly preserved fossils in lower part	140
Limestone, dolomitic and arenaceous, containing alternating thin layers of chocolate-brown shale and nodular chert; fossils fairly abundant in limestone but poorly preserved	91
Shale, brick-red	56
Conglomerate, with matrix of limestone containing rounded pebbles of chert, limestone, and sandstone	4
Shale, brick-red, alternating with shaly sandstone, with conglomerate made up of pebbles of Madison limestone resting on uneven surface of Madison limestone	80

INDIAN CREEK, MADISON VALLEY.

Indian Creek joins Madison River from the east a few miles south of Cameron. Its branches drain a rugged area containing numerous alpine peaks in the heart of the Madison Range. From a densely timbered basin in the Mesozoic rocks the upper waters of the stream unite and flow westward through a sharp canyon (Pl. XI, *A*) in pre-Cambrian rocks bordered on the east by Paleozoic rocks that dip steeply northeastward. In secs. 20 and 21, T. 8 S., R. 2 E., on the north canyon wall (locality 2, Pl. IX), there are complete exposures of strata from the Madison limestone to the top of the Kootenai, stratigraphically nearly 2,000 feet higher. A fault of large displacement cuts the lower Paleozoic strata at this point but does not affect the sequence of the higher strata. A condensed section of beds measured here is given below.

Section on Indian Creek, Mont.

	Ft.	in.
Kootenai formation:		
Limestone, gray, smooth textured, crowded with gastropods in basal portion	50	
Shale, ferruginous, with a few sandy layers and a layer of ocher-yellow blocky limestones, lavender-colored on fresh fracture	400	
Sandstone, quartzitic	38	
Shale, variegated red and brown	64	
Sandstone, coarse, with irregular conglomeratic layer in the midst, the pebbles mostly dark chert	32	
Shale and clay with carbonaceous layers	49	
Sandstone, coarse, arkosic, with undulating base	158	
Shale, yellowish gray, with sandy layers	59	
Shale, reddish, with sandy layers	109	
Ellis formation:		
Shale, bluish gray to green, with layers of impure limestone	98	
Sandstone, green, friable	14	
Limestone, granular, gray, rich in fossils	32	
Shale, greenish, weathering yellow	18	
Limestone, gray, sparingly fossiliferous	51	
Limestone, gray, shaly, richly fossiliferous	88	
Shale, calcareous, gray, fossiliferous	28	
Unconformity (?).		

Ellis formation—Continued.	Ft.	In.
Basal member of Ellis or possibly equivalent of Nugget sandstone of western Wyoming:		
Shale, ocherous, sandy, gypseous in upper part	89	
Shale, calcareous, sandy	12	
Limestone, impure, sandy	13	
Sandstone, cross-bedded, yellowish, friable	42	
Unconformity.		
Triassic marine beds:		
Shale, sandy, grading downward into thin-bedded limestone that weathers sepia-brown, closely resembling the Dinwoody of Wyoming, containing *Lingula* n. sp. and other fossils	102	
Phosphoria formation:		
Sandstone, dark gray, containing irregular chert layers and columnar rods of lighter-colored sandstone	65	
Chert in thin dark wavy layers	33	
Phosphatic beds:		
Phosphate rock, gray, coarsely oolitic		4
Limestone, dark gray		10
Shale		2
Phosphate rock, black, oolitic, friable, with 2 inches of shale near middle; 59.52 per cent tricalcium phosphate	2	11
Shale, carbonaceous	1	10
Phosphate rock, impure, containing fish bones		4
Sandstone, cherty	6	
Quartzite, dark gray		12
Shale		3
Limestone, sandy, containing phosphatized fossil fragments and travel-rounded chert pebbles		6
Quadrant quartzite:		
Sandstone, quartzitic, gray, cross-bedded, not measured.		

There is some question as to the lower limit of the Ellis formation in the preceding section. It seems clear that the position of the great unconformity is at the base of the yellow sandstone that rests on the Triassic marine beds, but the overlying shaly gypsiferous beds apparently represent continental sedimentation in Jurassic time prior to the encroachment of the Ellis Sea and if so would not appropriately be included in the Ellis. Possibly these gypsiferous beds and the yellow sandstone represent the Nugget sandstone of western Wyoming, as suggested in the diagram (fig. 14).

SNOWCREST MOUNTAINS.

The Snowcrest Mountains are west of Ruby River, about 20 miles a little west of south from Virginia City. The highest peaks, more than 10,000 feet in elevation, are capped by the resistant Quadrant quartzite. (See Pl. XI, *B*.) The most interesting features of the stratigraphy of this range are the unusual thickness of the Quadrant formation as compared with its thickness in the section in the Gravelly Range, 10 miles to the east, and the prominent development of the dark, richly fossiliferous limestone in its lower portion. The following fossils were identified by G. H. Girty, who regards them as of early Pennsylvanian age:

Lingula sp.
Lingulidiscina sp.
Schizophoria n. sp.
Derbya robusta?
Productus cora.
Productus aff. P. coloradoensis.
Productus aff. coloradoensis var.
Productus n. sp.
Spirifer rockymontanus.
Composita subtilita.
Hustedia mormoni.

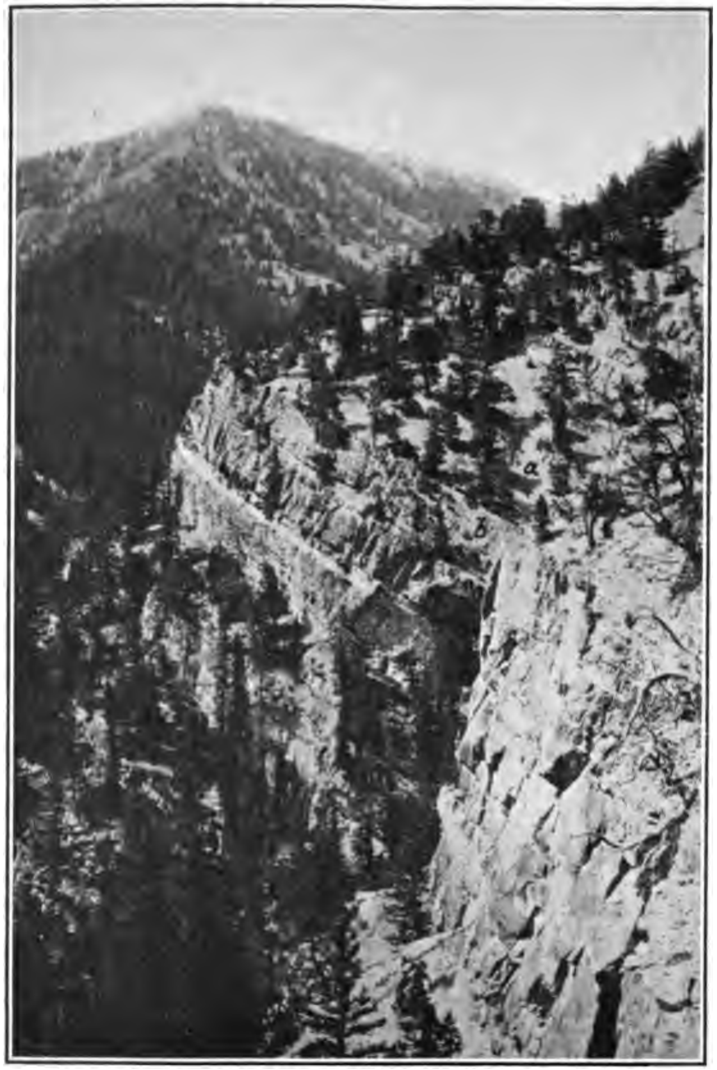
The subjoined section shows all but the uppermost beds of the Quadrant as measured in sec. 26, T. 10 S., R. 4 W. (locality 3, Pl. IX):

Section of Quadrant quartzite in Snowcrest Mountains, Mont.

	Feet.
Limestone, dolomitic, with gray sandy layers	80
Sandstone, quartzitic, gray, with two thin layers of brownish-mottled shale	207
Limestone, cherty, dolomitic, with thin sandy layers	29
Sandstone, quartzitic, gray, with thin layer of black shale in upper part and interbedded layers of dolomitic and smooth-textured dark-gray limestone	247
Limestone, dark gray, sparingly fossiliferous; several quartzite layers	55
Quartzite, pinkish	3
Limestone, dark gray, shaly to massive layers, with scattered brown to black chert nodules; fossils extremely abundant, especially in shaly limestone (see list above)	253
Rocks poorly exposed	50
Sandstone, conglomeratic at base, possibly basal member of Quadrant formation; approximate thickness	20
Rocks not exposed	25
Limestone of fissile shaly structure, rich in fossils. This is apparently a part of the Madison but represents a phase not found elsewhere to the east or southeast.	

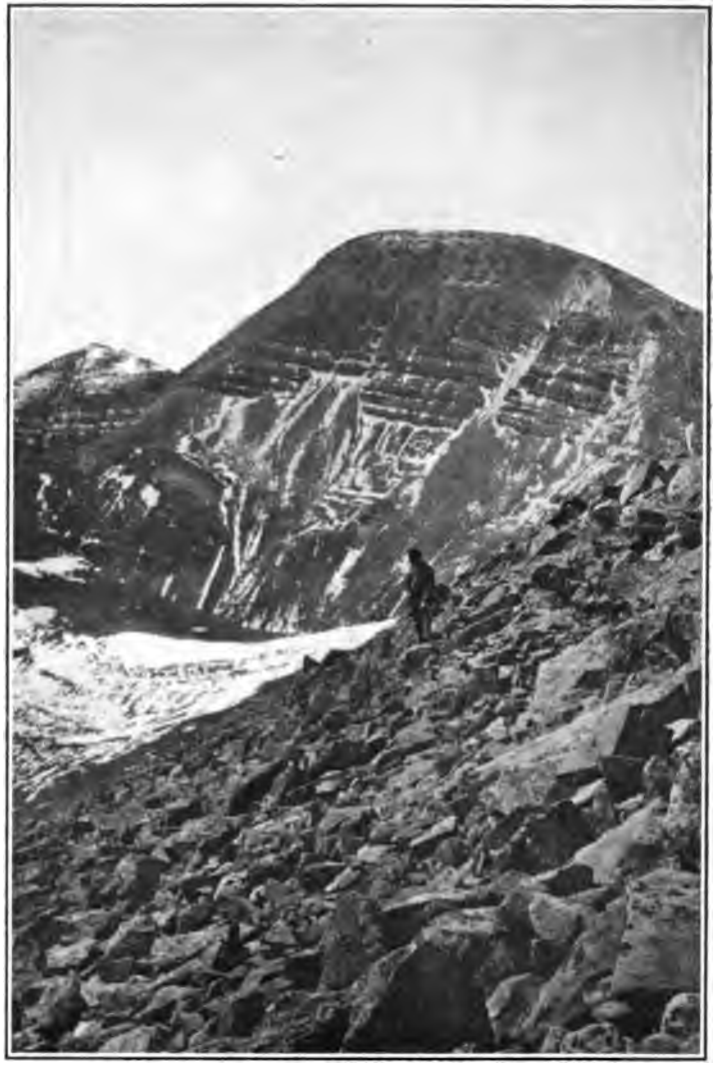
IDAHO-MONTANA STATE LINE OPPOSITE RED ROCK LAKES.

On the State line between Idaho and Montana, in the Centennial Range south of the Red Rock Lakes (Pl. XII), about 35 miles southeast of the locality in the Snowcrest Mountains above described, the Quadrant formation proper is greatly reduced in thickness, being



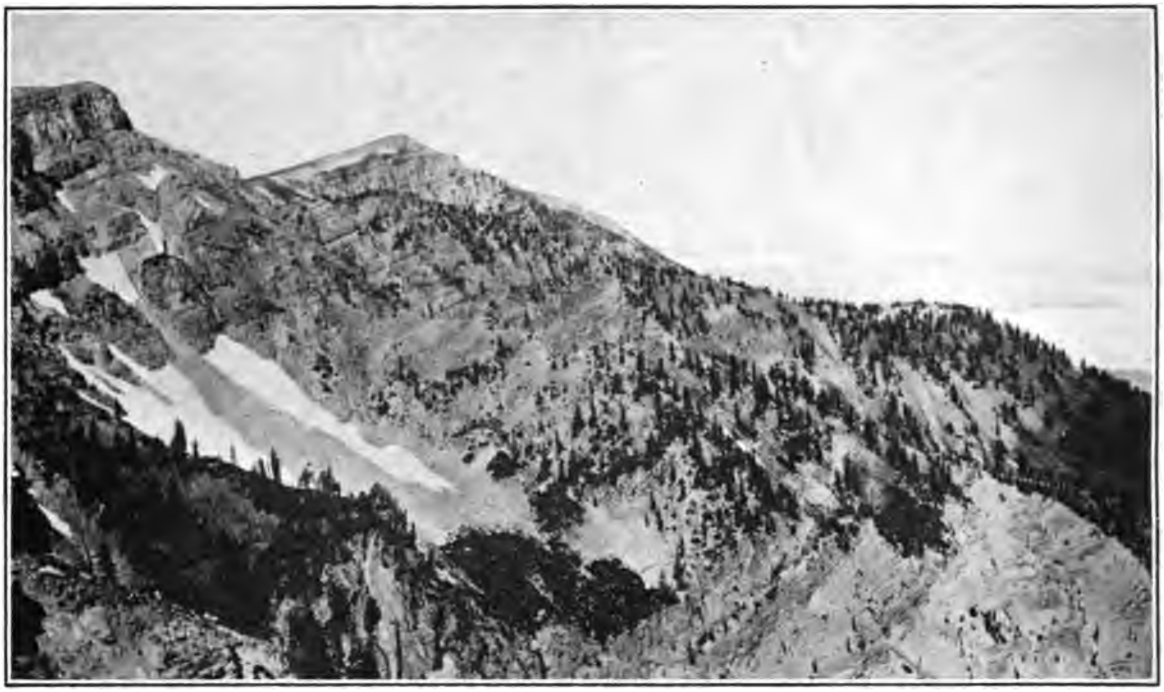
A. CANYON OF INDIAN CREEK, MADISON RANGE, MONT.

Showing cliffs of quartzite of the Phosphoria formation (*b*) overlain by shaly Mesozoic beds (*a*).



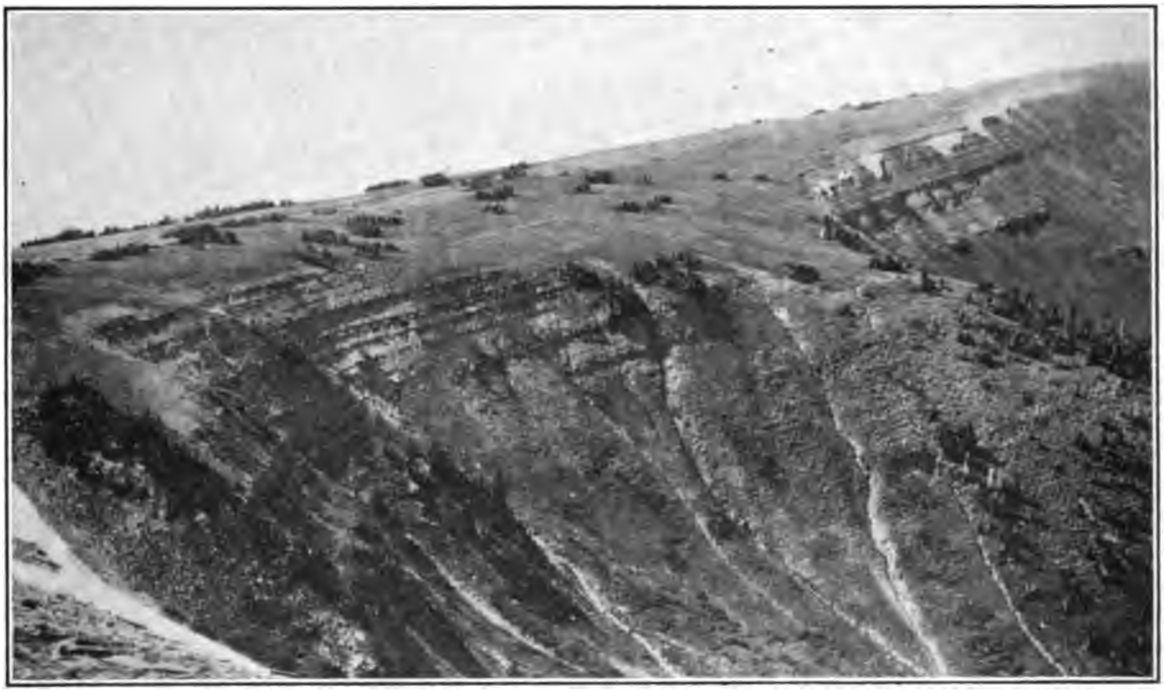
B. PRINCIPAL PEAK IN SNOWCREST RANGE, MONT.

Consisting of Madison limestone (lowest exposures in view), overlain by shaly limestone of the Quadrant quartzite capped by quartzitic beds which form the talus slopes in the foreground.



A. VIEW WESTWARD ALONG CREST OF CENTENNIAL RANGE FROM POINT NEAR MONTANA PRINCIPAL MERIDIAN.

Bed Rock Lakes in distance. The rocks are Phosphoria formation, Quadrant quartzite, and Madison limestone.



B. SHALY CALCAREOUS BEDS ALONG CREST OF CENTENNIAL RANGE, EQUIVALENT TO DINWOODY FORMATION OF WYOMING.

probably no more than 200 feet thick, as compared with 900 feet in the Snowcrest locality. The upper sandy beds and underlying fossiliferous limestone are present, however, and a fossil collection shows close relation with the fauna of the thick shaly limestone in the Snowcrest section. The red shale usually observed at the base of the Quadrant is absent, and there is only a few feet of ocherous sandy beds resting on the massive white saccharoidal Madison limestone.

The Phosphoria formation at this point resembles in lithology the beds exposed on Indian Creek but contains in addition a valuable bed of phosphate rock at the base, nearly 4 feet thick and carrying 70 per cent of tricalcium phosphate. This bed, which is evidently of clastic origin, consists chiefly of fragments of phosphatized shells of the fossil *Lingulidiscina*. At the base there is a few inches of quartz or chert conglomerate marking the lower limit of the Phosphoria formation.

QUADRANT MOUNTAIN, YELLOWSTONE PARK.

Quadrant Mountain, a prominent topographic feature in the northwestern part of Yellowstone National Park, presents bold exposures of the quartzitic beds which have been named Quadrant quartzite, as explained on pages 111–112. Below is given part of a section measured by Weed[1] at the southeast end of the mountain (locality 5, Pl. IX). The portion of the Teton assigned to the Phosphoria under the new classification is indicated.

Section on Quadrant Mountain, Yellowstone National Park.

[Measured by W. H. Weed.]

	Feet.
Teton:	
Sandstone, red and orange-colored, coarsely granular; weathers in blocks	15
Calcareous shale, dark slate-colored, fossiliferous.	5
Limestone, bright yellow, fissile, with platy débris, grading into yellow and red spotted calcareous sandstones below	40
Shales, light greenish drab, changing to red and grading into overlying beds	75
Conglomerate of red and gray quartz pebbles in limestone matrix	10
Cherty sandstone, the lower part without chert, is brown; slightly calcareous at base, becoming more so above [Phosphoria formation]	100
Quadrant:	
Limestone, dense, white, weathering same color	10
Sandstone and limestone in alternating bands	15
Limestone, light gray and dense and pure	12
Quartzite, pure white, thin bedded; forms a persistent band along face of mountain	6
Quartzite, more thickly bedded, white	65
Limestone, very light gray, somewhat dense, containing very small fragments of light-colored chert	10
Quartzite, white, calcareous, with intercalated bands of limestone carrying quartzite fragments	30
Limestone, light gray, with angular fragments of sandstone	5
Quartzite, white, weathering pink and rust color but appearing black when seen from a distance, owing to the growth of lichens upon it	130
Limestone, light gray, dense	2
Sandstone, well banded, white, saccharoidal	6
Sandstone, very calcareous, saccharoidal, white and rust color	10
Talus slope of sandstone blocks; also of cherty limestone	100

Additional sections measured at several places on Quadrant Mountain during the present investigation are given below. The Phosphoria exposures were found at the south end of The Pocket, a peculiar natural amphitheater cut into the plateau surface of the mountain top. Complete exposures of the Quadrant quartzite were found about 2 miles to the southwest, on the north face of Bannock Peak. (See Pl. XIII, *A*.)

Detailed section of Quadrant and higher formations on Quadrant Mountain.

	Ft.	in.
Triassic beds:		
Limestone, gray, thin bedded; weathers sepia-brown; grades up into shaly, sandy yellowish beds overlain by red shale; *Lingula* n. sp. is plentiful in the limestone	60+	
Phosphoria formation:		
Sandstone, dark gray, with scattered chert nodules	15±	
Chert, in ropy masses and wavy layers, with irregular sandy layers in upper part	30	
Sandstone, dark gray, with cauda-galli markings on bedding and scattered siliceous nodules and ropy masses; fishbones plentiful	9	
Phosphatic rock, gray, with green specks	1	2
Sandstone, dark gray, with markings; chert and fishbones similar to those in 9-foot sandstone above	23	
Quartzite, dark gray	16	
Phosphate rock, sandy, resinous; has brown appearance on fresh fracture; contains fragments of *Lingulidiscina*	3	2
Quartzite, gray, phosphatic in upper part	18	
Quadrant quartzite:		
Limestone, dolomitic, white, finely crystalline	7	
Sandstone, gray, cross-bedded	16	
Limestone, dolomitic, white, finely crystalline	23	

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[1] U. S. Geol. Survey Mon. 32, pt. 2, p. 34, 1899.

Quadrant quartzite—Continued.	Ft.	in.
Sandstone, quartzitic, alternating with sandy dolomitic beds; poorly preserved fossils plentiful near base	350	
Shale, red, sandy, slightly calcareous	11	
Sandstone, conglomeratic, yellow and red, resting on Madison limestone	18	

The beds above the Quadrant quartzite in this section constitute the Teton formation.

FORMATIONS IN WEST-CENTRAL WYOMING.

The sequence of late Paleozoic and early Mesozoic formations in west-central Wyoming is represented in the following table. Their probable equivalence with the section to the northwest in Yellowstone Park and Montana is indicated in Plate X.

Late Paleozoic and early Mesozoic formations in west-central Wyoming.

	Feet.
Sundance formation (Jurassic), limestone, green shale, and sandstone	200- 300
Chugwater formation (Triassic), largely red sandy shale, with sandstone and more or less gypsum	800-1,400
Dinwoody formation (Triassic), shaly brownish fossiliferous limestone	50- 200
Park City formation (Permian and Pennsylvanian), fossiliferous limestone and shales	150- 225
Tensleep sandstone (Pennsylvanian)	200- 500
Amsden formation (Pennsylvanian and late Mississippian), sandstone, limestone, and shale	200- 300

It has been shown by the writer[1] that although the Chugwater red beds are in large part Triassic, the lower portion in the Big Horn Mountains and elsewhere in central Wyoming is of earlier Triassic, Permian, and Pennsylvanian age and was deposited contemporaneously with the marine Triassic (Dinwoody) and Permian and Pennsylvanian (Park City) beds to the west.

AMSDEN FORMATION AND TENSLEEP SANDSTONE.

The Amsden formation, which rests on the Madison limestone, is somewhat similar in lithology to the lower portion of the Quadrant quartzite of Montana, with which it is correlated, but at no place has it been found to contain richly fossiliferous beds, such as have been discovered in Montana. In the western part of the Wind River Mountains the Amsden consists of massive white sandstone at the base, overlain by interbedded gray to yellowish shale, sandstone, and thin beds of limestone. Some of the shale beds are deep red.

The Tensleep consists almost entirely of sandstone, with a few interbedded dolomitic layers that locally contain marine fossils. The beds correspond so closely in position, thickness, and lithology with the upper portion of the Quadrant quartzite that there is no question as to their correlation. It is suggested also that the Tensleep may be in part equivalent to the Weber quartzite of southeastern Idaho and Utah.

PARK CITY FORMATION.

Above the Tensleep sandstone in the Wind River Mountains is a sequence of prevailingly calcareous beds correlated by Blackwelder[2] with the Park City formation of Utah on the basis of paleontologic and lithologic evidence. The Park City beds, together with overlying calcareous brownish shaly beds of Triassic age, constitute the Embar formation of Darton,[3] who applied this name to strata believed to be of "Permo-Carboniferous" age, lying between the Tensleep sandstone and Chugwater red beds at a locality in the Owl Creek Mountains. This grouping into one formation of beds of Pennsylvanian, Permian, and Triassic age and of widely different lithology is comparable to the grouping of the beds in the Teton formation of Yellowstone Park, and the only reason for retaining Embar as a formation name is its convenience as a term for use in areas where the Dinwoody and Park City can not be differentiated.

The portion of the Embar formation equivalent to the Park City beds in the Wind River and Owl Creek mountains (see Pl. XIII, *B*) consists largely of limestone with calcareous shale and nodular chert. The general sequence is as follows:

Generalized section of Park City formation in Wind River and Owl Creek mountains, Wyo.

Siliceous greenish limestone grading up into gray resistant limestone, with abundant fossils including *Derbya*, *Pseudomonotis*, *Leioclema*, and *Spiriferina pulchra*.

Nodular greenish phosphatic chert interbedded with many shale laminae.

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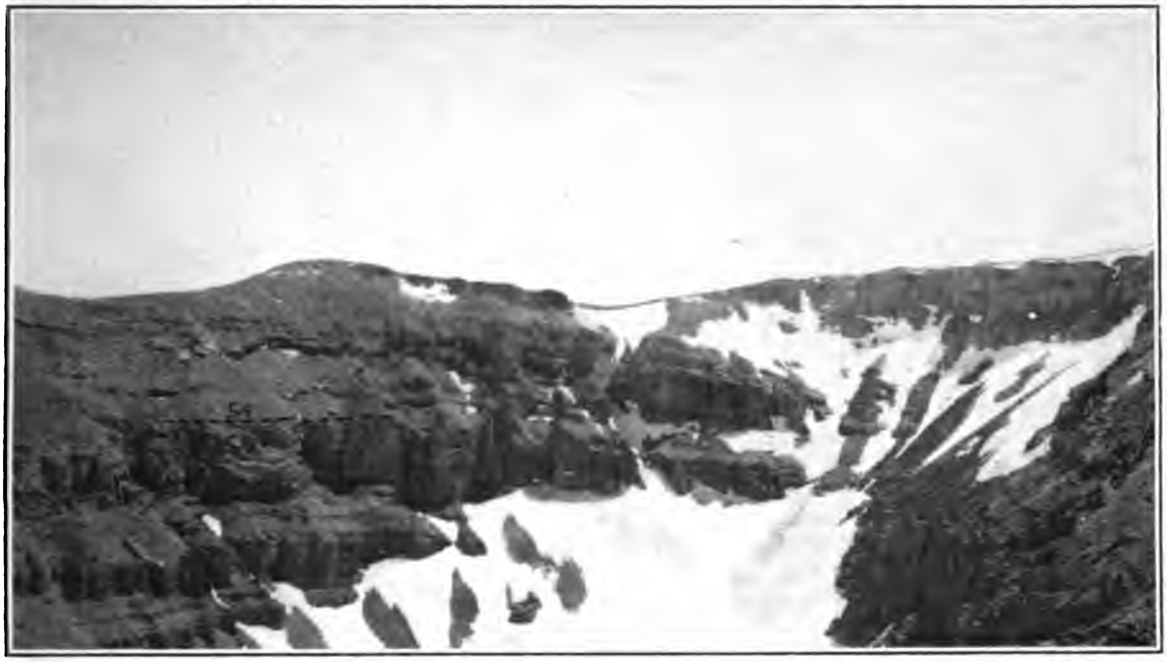
[1] Condit, D. D., Relations of the Embar and Chugwater formations in central Wyoming: U. S. Geol. Survey Prof. Paper 98, pp. 263-270, 1916.

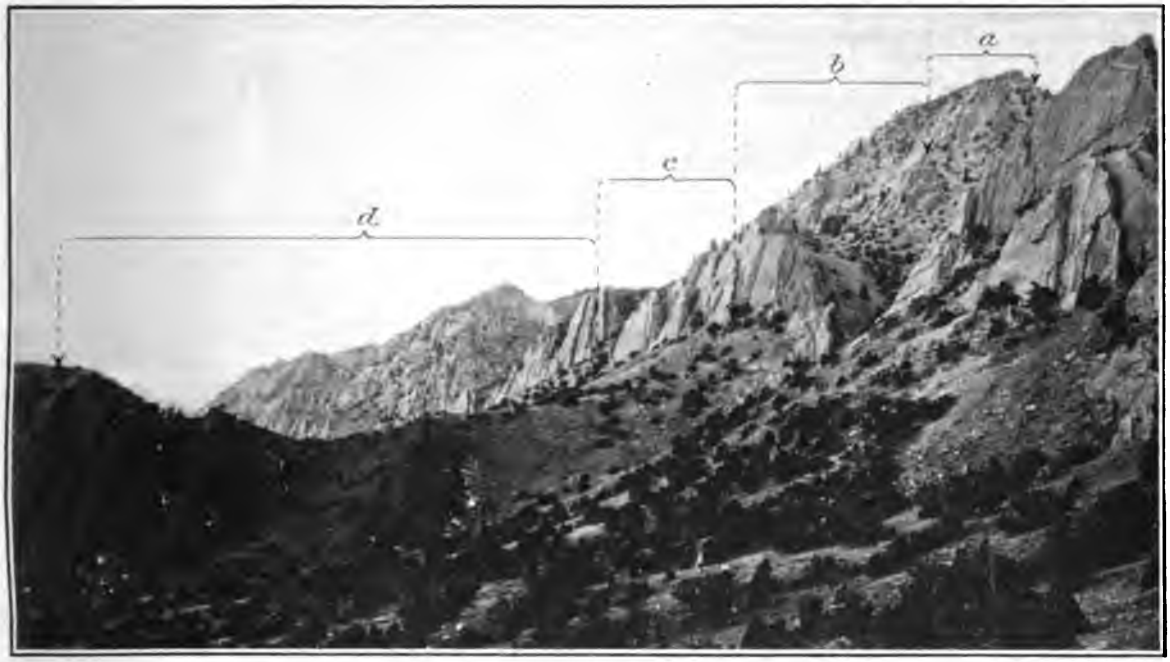
[2] Blackwelder, Eliot, Stratigraphy of the Wind River Mountains, Wyo.: U. S. Geol. Survey Bull.—— (in preparation).

[3] Darton, N. H., Geology of the Bighorn Mountains: U. S. Geol. Survey Prof. Paper 51, p. 35, 1906.



A. NORTH FACE OF BANNOCK PEAK, YELLOWSTONE NATIONAL PARK.

Showing Madison limestone (Cm) and Quadrant quartzite (Cq) at head of cirque valley.



B. UPTURNED BEDS ON SOUTH SLOPE OF OWL CREEK MOUNTAINS, WYO., NEAR SHOTGUN CREEK, T. 7 N., R. 1 E.

a, Tensleep sandstone, forming highest hills; *b*, Park City formation, with resistant upper limestone member; *c*, shale of Dinwoody formation, mostly covered by talus; *d*, shaly red beds of Chugwater formation.

Phosphatic shale of sepia-brown color, with one or more layers of oolitic phosphate rock and phosphatic limestone at the base.

Limestone with geodes, chert masses, and many fossils, among which are *Productus nevadensis*, Leioclema, *Spiriferina pulchra*, and *Productus subhorridus*.

Argillaceous shaly limestone and sandy calcareous shale of yellowish color.

Dolomitic gray fossiliferous limestone, resting with slight unconformity on the Tensleep sandstone.

Paleontologic data recently presented by Branson[1] support the belief of Girty that the lower portion of the Park City beds is of Pennsylvanian age. Branson's conclusions are the result of study of both vertebrate and invertebrate fossils.

DINWOODY FORMATION.

The name Dinwoody formation has been adopted for the upper shaly portion of the Embar on the suggestion of Blackwelder, from Dinwoody Canyon, in the Wind River Mountains, where the formation, about 200 feet thick, consists of pale-green to white clay and shaly limestone that weather brown and contain obscure pelecypod shells. The Park City and Dinwoody beds found at this locality are described by Blackwelder in an unpublished bulletin on the stratigraphy of the Wind River Mountains. The consensus of opinion of several observers is that the Dinwoody beds are to be correlated with the Woodside shale (Lower Triassic) of southeastern Idaho. The beds are lithologically identical with strata in the middle portion of the series of beds in Yellowstone Park designated the Teton formation by Weed.

A complete section of the Embar measured by Blackwelder[2] at Dinwoody Canyon is given below.

Section in Dinwoody Canyon, Wyo.

	Ft.	in.
Dinwoody formation:		
Pale-green to white clay, with local sandy and calcareous beds, overlain conformably by bright-red sandy shale of the Chugwater formation	130	
Gray shaly limestone, weathering brown	28	
Alternate calcareous and sandy shale and argillaceous sandstone in thin beds	12	
Dark argillaceous limestone with shale partings containing many obscure pelecypod shells	10	
Park City formation:		
Grayish sandy shale, shaly limestone, and shaly sandstone, in alternate beds	75	
Massive gray crystalline limestone with fossil Bryozoa and brachiopods	16	6
Nodular greenish-gray clay, greenish limestone, and chert; *Spiriferina pulchra*, *Hustedia meekana*, *Derbya* sp., crinoids, and Bryozoa in abundance	6	
Alternating sepia-brown phosphatic and calcareous shale and shaly limestone, with thin beds of chert near the top; abundant *Productus nevadensis?* near the base	35	6
Brown shale and soft nodular black and gray phosphate rock interlaminated (30.5 per cent tricalcium phosphate)	1	8
Dark greenish-gray oolitic and argillaceous phosphate rock (41 per cent phosphate)	1	
Gray to sepia-brown shale, full of oval nodules somewhat more calcareous; abundant *Spirifer*, *Productus*, etc. (average 8.5 per cent phosphate)	12	5
Hard greenish-brown phosphatic limestone, with glauconite grains (23.7 per cent phosphate)		7
Brown argillaceous limestone and calcareous shale, nodular, as above; abundant *Productus nevadensis*, *P. cora*, *P. subhorridus*, *Spiriferina pulchra*, *Pugnax utah*, Bryozoa, etc. (8 per cent phosphate)	6	
Dark-drab or brown fetid limestone in massive beds; upper layers crowded with Bryozoa	21	
Green clay shale with thin beds of chert and platy gray limestone	43	
Gray speckled phosphatic sandstone	1	
Earthy white sandstone	2	
Greenish-gray speckled phosphatic sandstone containing *Lingulidiscina utahensis*, etc. (27.4 per cent tricalcium phosphate)	2	2½
Light-gray earthy limestone	1	9½
Dark-green shale	1	3½
Pale-gray smoky dolomite with seams of black chert and pores full of black bitumen	25	
White calcareous sandstone and conglomerate of chert pebbles; lies with obscure unconformity upon the Tensleep sandstone	1	7

CHUGWATER FORMATION.

The Chugwater red beds, 800 to 1,450 feet thick in west-central Wyoming, present problems in sedimentation that have engaged the attention of a number of workers who are not in agreement as to the origin of these beds. Among their striking features are the uniformity in thickness and texture of individual members over wide areas; the prevalence of ripple marks on horizontal beds through much of the formation; the absence of sun cracks and fossils of land animals except in the upper portion; and the extensive occurrence of gypsum beds near the top. It is not the purpose of this paper to consider in detail the peculiarities of the Chugwater or the different hypotheses concerning its origin. It is evident, however, that mature conclusions can be reached only after a detailed study of the red beds throughout Wyoming and adjacent areas. The question of age alone illustrates this point. In western Wyoming the lowest red beds overlie marine fossil-bearing brown shales of Triassic age that are regarded by several observers as equivalent to the Lower Triassic Woodside shale of Idaho. Furthermore, it is suspected that the lower Chugwater beds of western Wyoming grade laterally into the marine Thaynes limestone of Idaho, which are of Lower Triassic age, or at least that they represent partial-time equivalents of these beds.

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[1] Branson, E. B., The lower Embar of Wyoming and its fauna: Jour. Geology, vol. 24, pp. 639-664, 1916.

[2] Blackwelder, Eliot, A reconnaissance of the phosphate deposits in western Wyoming: U. S. Geol. Survey Bull. 470, pp. 476-477, 1911.

A fossil collection made by Darton[1] in the Big Horn River canyon near Thermopolis, Wyo., is of interest in this connection. The fossils obtained in a limestone 150 feet below the top of the formation were found by G. H. Girty to include *Natica lelia*, *Bakewellia*, *Pleurophorus*, and *Aviculipecten*, undoubted marine types, constituting a fauna which is referred with considerable confidence to the Triassic. This occurrence is of additional interest as indicating the marine origin of a portion of the Chugwater, as contended by Branson.[2]

In the Big Horn Mountains, in the central part of the State, the lowest red beds of the Chugwater have been shown by the writer[3] to be of late Pennsylvanian age.

The age of the uppermost beds of the Chugwater formation is uncertain. Wherever present in Wyoming they are overlain by the Sundance formation, which is Upper Jurassic, but it is a question whether the deposition of the gypseous shale, cross-bedded sandstone, and nonmarine limestone characteristic of the upper part of the Chugwater may not have been largely contemporaneous with the early Jurassic base-leveling so plainly recorded in the truncated beds to the north, in Montana.

SUNDANCE FORMATION.

The Sundance formation of Wyoming is regarded as the equivalent of the Ellis in Montana, with which it agrees fairly well in lithology, thickness, and fossil content. The Sundance consists largely of greenish calcareous to sandy shale, with a resistant dark-gray limestone near the middle. Both the shale and the limestone are richly fossiliferous, and the most characteristic species are *Belemnites densus*, *Gryphaea calceola*, and stem segments of the crinoid *Pentacrinus asteriscus*.

RECORD OF JURASSIC BASE-LEVELING.

The most striking evidence of prolonged erosion in Jurassic time is furnished by the contact of the late Jurassic marine beds (Ellis) with successively older formations as followed northward across Montana. This feature is graphically shown in figure 14. The substrata along the Idaho-Montana State line near Yellowstone Park are limestone or red beds of Triassic age, and successively lower formations appear northward to Elkhorn mining camp, about 20 miles south of Helena, where the substrata are beds probably 75 feet below the top of the Phosphoria formation. Fisher[4] has stated that in places in the Great Falls region, in northern Montana, the Ellis rests on the Madison limestone.

Study of the erosion surface from place to place reveals the presence of peculiar yellowish earthy sandstone, ferruginous gypseous shale, and local limestone beds, all making up a motley aggregate related neither to the overlying Ellis nor to the underlying formations. These heterogeneous materials constitute the sedimentary record of events that preceded or accompanied the advance of the sea from the northwest in late Jurassic time. Their thickness, ranging from a few feet to little more than 100 feet, is direct evidence of the slight relief of the land surface, the inequalities of which were leveled to form the floor upon which the marine Ellis beds were deposited.

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[1] Darton, N. H., Geology of the Bighorn Mountains: U. S. Geol. Survey Prof. Paper 51, p. 40, 1906.

[2] Branson, E. B., Origin of the Red Beds of western Wyoming: Geol. Soc. America Bull., vol. 26, pp. 217-230, 1915.

[3] Condit, D. D., Relations of the Embar and Chugwater formations in central Wyoming: U. S. Geol. Survey Prof. Paper 98, pp. 263-270, 1916.

[4] Fisher, C. A., Geology of the Great Falls coal field, Mont.: U. S. Geol. Survey Bull. 356, p. 27, 1909.

The thickness of strata removed by Jurassic erosion in northern Montana may have been 2,000 feet, if the Chugwater red beds once extended over that area. The extent to which the Chugwater was eroded in Wyoming is not evident, but it seems probable that in the west-central part of the State, where the beds are 1,400 feet thick, they remain almost intact, and that the upper portion, including the gypseous beds, may be in part a product of Jurassic sedimentation.

The disposition of the great mass of material stripped from the northern area is a matter of speculation, but in the writer's opinion this erosion may have furnished the sediments of the shale and sandstone series of southeastern Idaho lying between the marine Lower Triassic (Thaynes limestone) and marine Upper Jurassic (Twin Creek limestone). It is probable that in the meanwhile the Wyoming area, a low, nearly level plain, which was intermittently occupied by small bodies of water and in which neither erosion nor deposition of considerable magnitude occurred, furnished the conditions necessary for the formation of extensive but variable gypsum and limestone beds.

NEW GRAPHIC METHOD FOR DETERMINING THE DEPTH AND THICKNESS OF STRATA AND THE PROJECTION OF DIP.

By Harold S. Palmer.

INTRODUCTION.

Geologists, both in the field and in the office, frequently encounter trigonometric problems the solution of which, though simple enough, is somewhat laborious by the use of trigonometric and logarithmic tables. Charts, tables, and diagrams of various types for facilitating the computations have been published, and a new method may seem to be a superfluous addition to the literature. However, it is felt that the simplicity and accuracy of diagrams such as are presented in this paper warrant the addition. The alinement diagram is used to a very considerable extent by engineers, especially mechanical engineers. The principle of the alinement diagram is explained herein, but rigorous demonstration is not attempted.

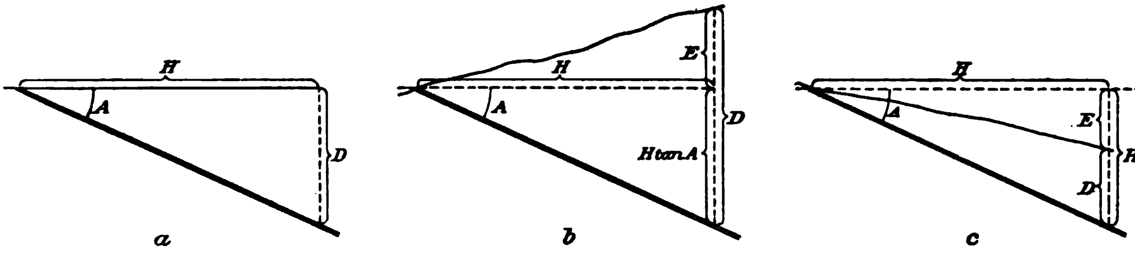


FIGURE 15.—Diagram showing three cases in computing depth.

Alinement diagrams are given for the following problems, which are numbered to agree with the numbering of the diagrams. The charts published herewith are suitable for use.

I. To find the depth to a stratum, given the dip of the stratum, the horizontal distance from the outcrop, and the difference in elevation between the outcrop and the point at which the depth is desired. (See fig. 15.) The formula is

$$D = H \tan A \pm E \ldots\ldots\ldots\ldots (1$$

in which D = depth to stratum, H = horizontal distance from the outcrop, A = dip, E = difference in elevation.

(Note.—Diagram I may be used not only for the problem above stated but also to obtain the difference in elevation between two points by omitting E and letting D equal the difference in elevation, H the horizontal distance, and A the vertical angle.)

II. To find the thickness of a stratum, given the dip of the stratum, the horizontal distance across its outcrop at right angles to the strike, and the difference in elevation of the upper and lower boundaries of the stratum. There are three cases, depending on the relation of the dip of the beds to the slope of the ground. (See fig. 16, *a*, *b*, and *c*.)

Case 1, where the ground is level. By inspection of figure 16, *a*, it is seen that the formula is

$$T = H \sin A \ldots\ldots\ldots\ldots (2)$$

in which T = thickness, H = horizontal distance from outcrop, and A = dip.

Case 2, where the ground slopes opposite to the dip. In figure 16, *b*,

$$T = m + l$$

but

$$m = H \sin A$$

Now

$$l = E \cos A$$

or, as

$$\cos X = \sin (90^\circ - X)$$

$$l = E \sin (90^\circ - A)$$

Therefore

$$T = H \sin A + E \sin (90° - A) \text{ . . . . . } (3)$$

in which T, H, and A have the same values as before, and E is the difference in elevation.

Case 3, where the ground slopes with the dip. In figure 16, *c*, $T = m - l$; making the same substitutions as in case 2, we find

$$T = H \sin A - E \sin (90° - A) \text{ . . . . . } (4)$$

in which T, H, A, and E have the same values as before.

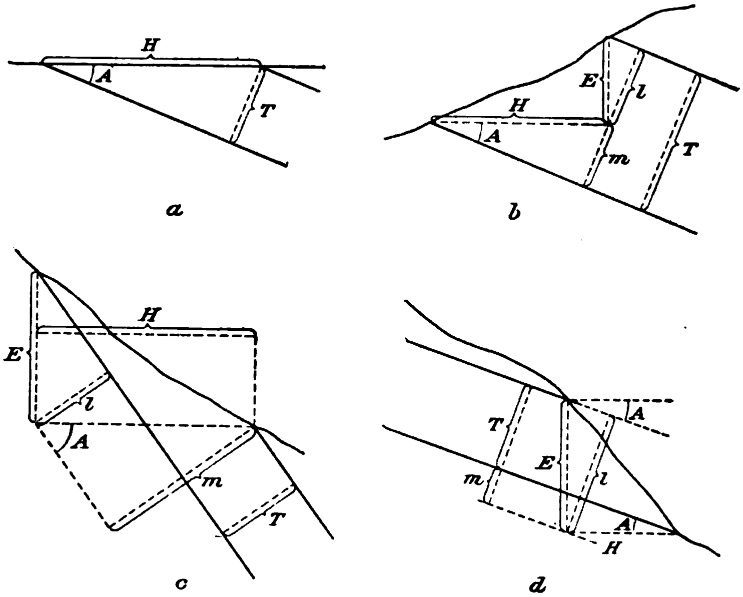


FIGURE 16.—Diagram showing three cases in computing thickness.

The above formula is strictly true only where the dip of the beds is greater than the slope of the ground. (See fig. 16, *d*.) Where the dip is less than the slope the formula becomes

$$T = E \sin (90° - A) - H \sin A \text{ . . . . . } (4a)$$

The difference is algebraic and not arithmetic, so that the formula is practically workable for either subcase.

III. Projection of dips—that is, to find the slope of the trace of an inclined plane upon a vertical plane oblique to the strike. Consider figure 17, *a*, which is a plan or map; at A is an inclined plane the strike and dip of which are shown in the conventional way, and along S–P is a vertical plane upon which this dip is to be projected. B is the angle between the strike and the section plane. In figure 17, *b*, A is a dip whose projection on SPQR, the plane of a supposed structure section, is desired. C is the desired projection of A. B is the angle between the plane of the section and the strike of the beds, and angle PFS is a right angle. The plane PFS is horizontal and the lines PQ, FG, and SR are normal to it and of equal length, so that the triangle QGR is also horizontal and is equal to PFS.

Now,

$$FS = PS \sin B$$

$$FS = FG \cot A$$

$$PS = PQ \cot C$$

Therefore

$$FG \cot A = PQ \cot C \sin B$$

but

$$FG = PQ$$

so

$$\cot A = \cot C \sin B$$

and, as the tangent is the reciprocal of the cotangent,

$$\frac{1}{\tan A} = \frac{1}{\tan C} \sin B$$

$$\tan C = \tan A \sin B \text{ . . . } (5)$$

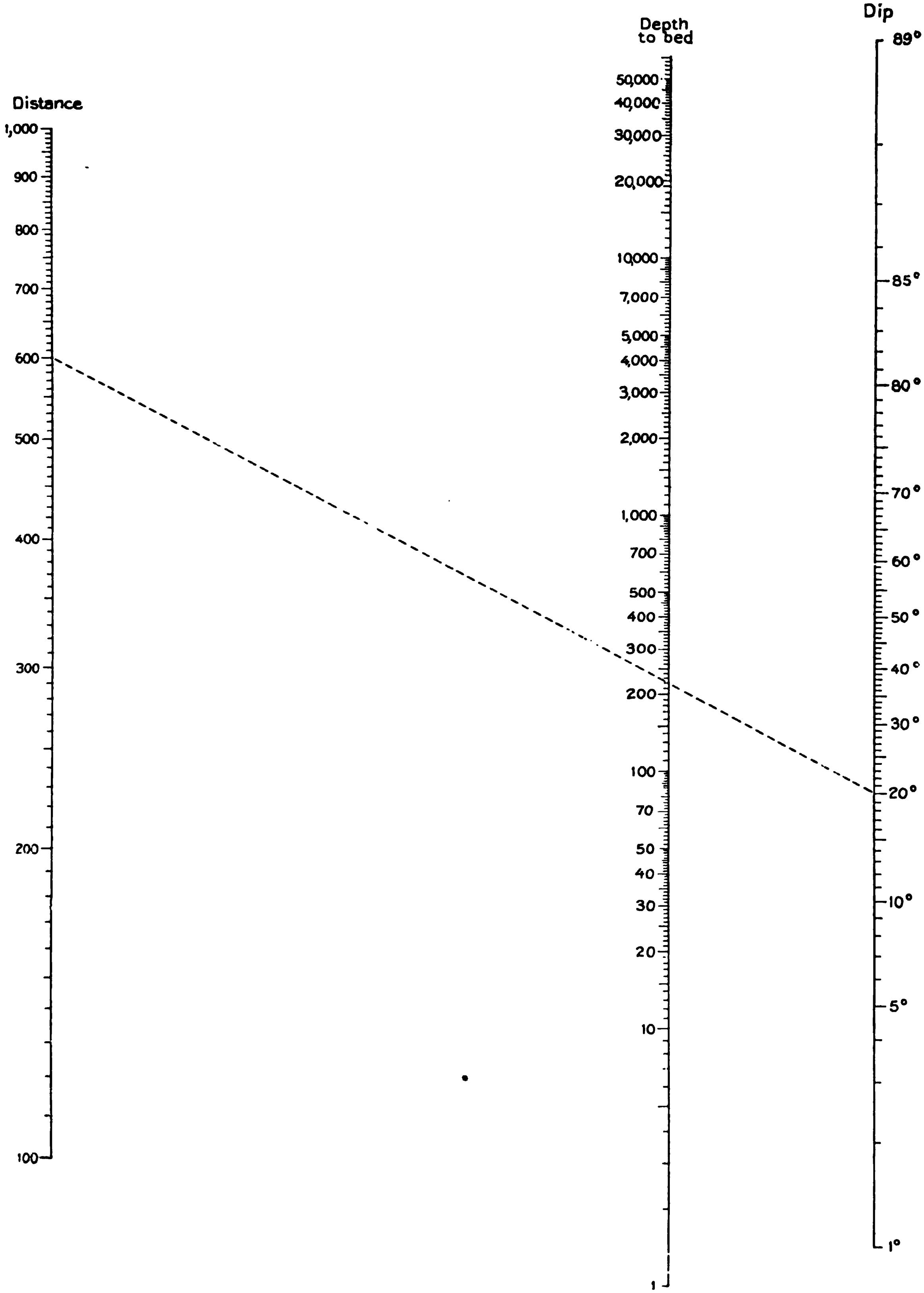
in which C = dip of the projected angle, A = dip of the bed, B = angle between strike and plane of section.

USE OF THE ALINEMENT DIAGRAMS.

The alinement diagram is worked in an extremely simple way. The points on the outer scales representing the given quantities are joined by a line, and the unknown quantity, or result, is read at the intersection with the middle scale. Interpolation between the values marked on the scales is effected just as on a slide rule. It is suggested that the edge of a draftsman's transparent triangle or a piece of slender black thread be used for projecting the cross line.

USE OF THE DEPTH DIAGRAM.

In using the depth diagram (Pl. XIV and problem I), find the point on the left-hand scale that represents the distance from the outcrop to the point at which the depth is desired, and join it to the point on the right-hand scale that



ALINEMENT DIAGRAM I, FOR COMPUTING DEPTH.

represents the dip of the beds. At the intersection of the line determined by these points with the middle scale the depth may be read. The dotted line on Plate XIV shows the solution when the distance is 600 feet and the dip 20°. The depth to the stratum is found to be 220 feet.

The above rule holds only if the surface is level. If the point at which the depth is to be determined is higher than the outcrop, the difference in their elevation is added to the depth as read by the above-described method. If the outcrop is the higher of the two points, the difference of elevation is subtracted from the reading.

The diagram may be used for the converse problem, namely, to find the dip of the bed when the depth and distance from the outcrop are given. In this case the given quantities are set on the middle and left scale, and the line joining them is produced till it cuts the right scale, at which the dip is read. Another converse problem arises when the distance from the outcrop is unknown but the dip and depth to the stratum are known. In this case known points on the right and middle scale are joined by a line the extension of which gives the result at its intersection with the left scale.

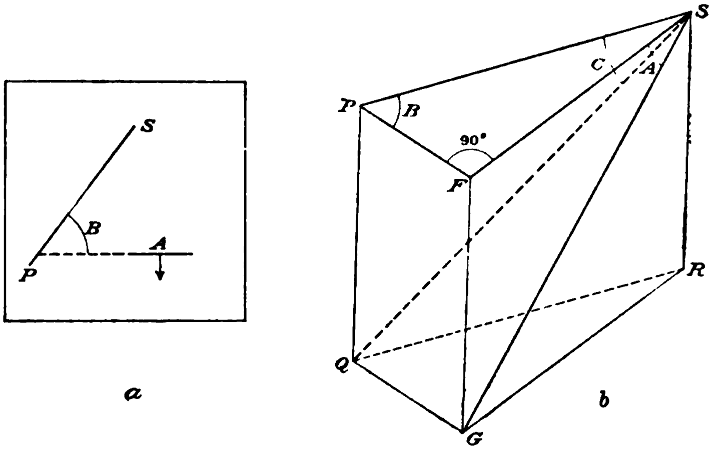


FIGURE 17.—Diagram for derivation of formula for projected dip.

USE OF THE THICKNESS DIAGRAM.

In using the thickness diagram (Pl. XV and problem II), find the point on the left scale that represents the width of the outcrop and join it to the point on the right scale that represents the dip of the beds. At the intersection of the line determined by these points with the middle scale the thickness may be read.

The above rule holds only if the surface is level. A correction must be added if the ground surface slopes in the opposite direction to the dip, and the same correction must be subtracted if the surface slope and the dip are in the same direction. This is the correction E sin (90°−A) in formulas (3) and (4). Subtract the dip from 90° and find the corresponding point on the right scale. Join it to the point on the left scale that represents the difference in elevation of the higher and lower boundaries of the outcrop, and at the intersection of the connecting line with the middle scale read the correction. The correction is added or subtracted as directed above.

In Plate XV the broken line shows the first step in solving the problem when the horizontal width of the outcrop is 600 feet and the dip is 20°. The thickness is read on the middle scale as 206 feet. The dashed line shows the correction to be introduced if the difference in elevation between the two edges of the outcrop is 50 feet. As there is no 50-foot graduation on the left scale, the decimal point is shifted to the right and the 500-foot graduation is joined by a line to the 70° mark on the left scale (90°−20°=70°). The reading is 470 feet, but the decimal point must be shifted back, so the true correction is 47 feet. Then if the bed dips "into the hill" the thickness is 206+47=253 feet; if it dips "with the hill" the thickness is 206−47=159 feet.

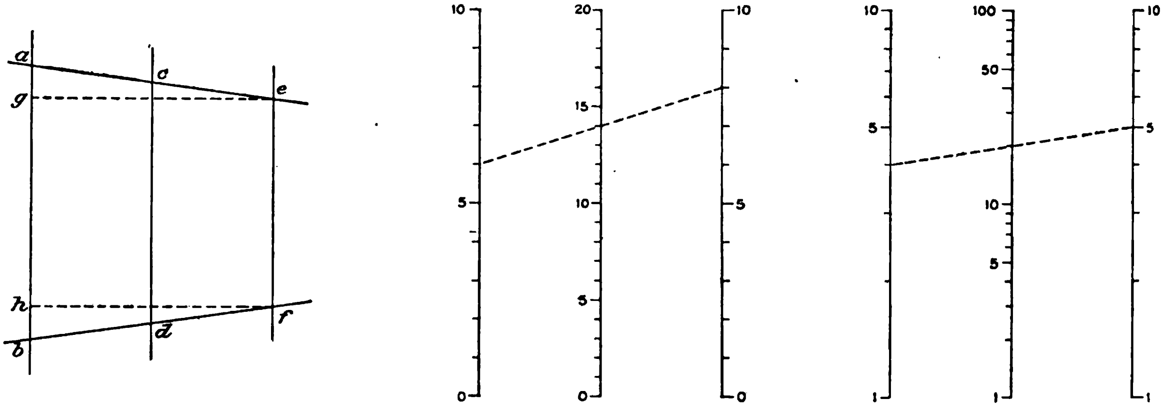
Like the depth diagram, the thickness diagram has converse uses, but they can be applied only when the ground surface is level. Thus if the width of the outcrop and thickness of the bed are known the dip can be computed, or if the dip and thickness are known the width of outcrop can be computed.

USE OF THE PROJECTION DIAGRAM.

In using the projection diagram (Pl. XVI and problem III) find the point on the left scale that represents the dip and the point on the right scale that represents the angle between the strike and the plane upon which the dip is to be projected. Join these points by a line, and at its intersection with the middle scale read the projected dip. As this problem involves only one case there are no corrections to be added or subtracted.

In Plate XVI the broken line shows the solution of the problem of projecting a dip of 43° upon a plane at an angle of 35° to the strike. The result, 28°, is read on the middle scale.

As with the other diagrams, the converse problems may be solved. Thus, if the trace of a bed along a vertical plane and the angle between the strike and the vertical plane are set on the middle and right scales, respectively, the dip of the plane may be read on the left scale. Again, if the dip of a bed and the slope of its trace on a vertical plane are known, and these points are set on the left and middle scales, respectively, the angle between the strike and the vertical plane may be read on the right scale.



a *b* *c*

FIGURE 18.—Diagram showing three stages in derivation of principle of the alinement diagram.

PRINCIPLE OF THE ALINEMENT DIAGRAM.

The alinement diagram is a device by means of which certain arithmetic processes (addition, subtraction, multiplication, division, involution, and evolution) may be mechanically or graphically performed. It is similar in principle to the slide rule in that by means of it distances proportional to numbers or to logarithms are mechanically added, subtracted, multiplied, or divided, but this work is done by a different mechanical process. It differs further from the slide rule in that each diagram is good for only one formula, whereas the slide rule is applicable to many formulas.

Consider figure 18, *a*, in which *ab*, *cd*, and *ef* are parallel lines cut by two secants, *ace* and *bdf*. From *e* and *f* drop two lines, *eg* and *hf*, perpendicular to *ab*. By inspection of the diagram it is seen that

$$cd = \tfrac{1}{2}(ab + ef)$$

This equation is equivalent to saying that the space cut off on the middle line is equal to half the sum of the spaces cut on the outer lines.

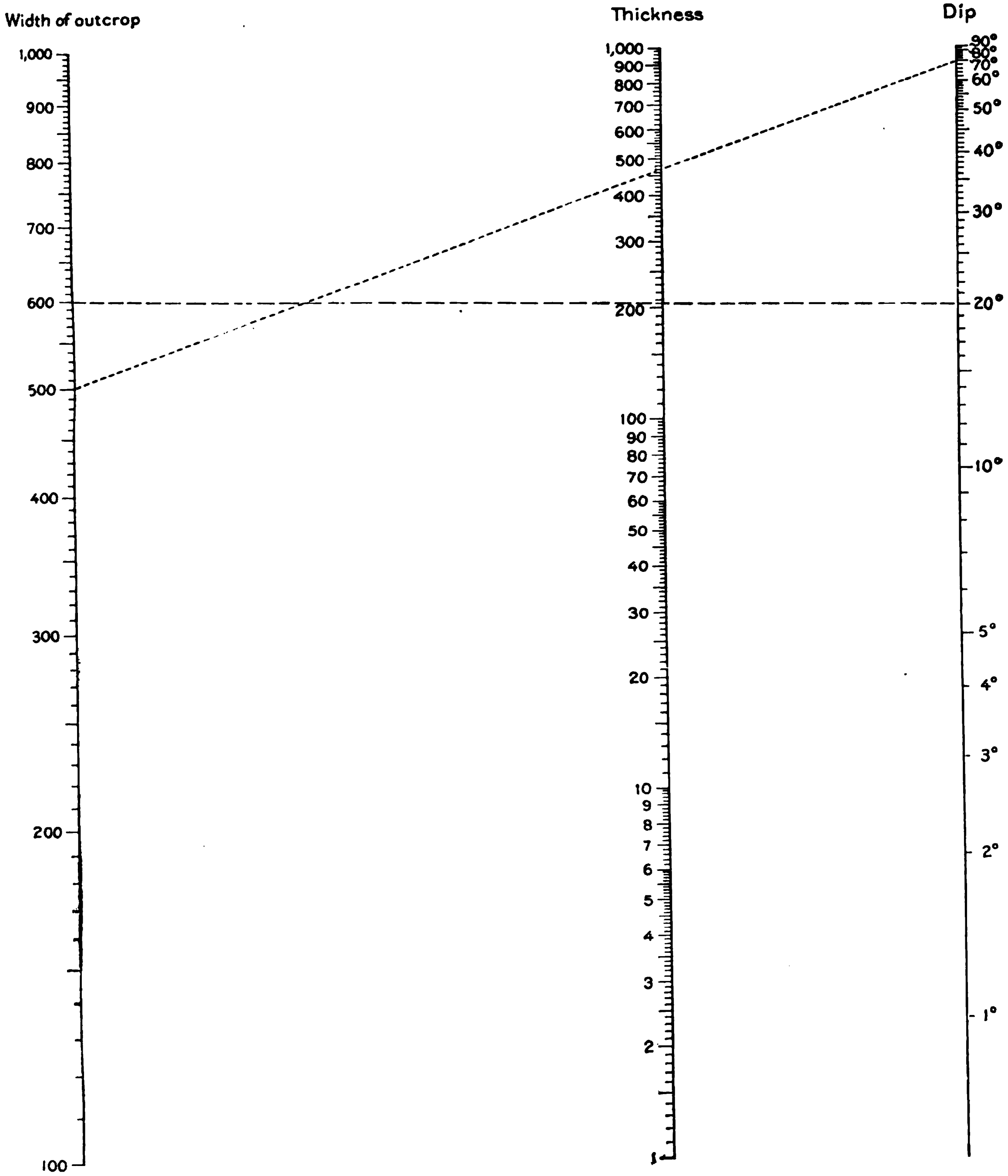
Now, if, as in figure 18, *b*, the outer lines are graduated evenly with equal divisions and the middle line is graduated with divisions half as great, addition can be graphically performed. The bases of the three scales are put on the same level for convenience only. The secant line is taken so as to cut off six divisions on the left scale and eight on the right scale. It must, perforce, cut 14 divisions on the middle scale, and the addition of 6 and 8 is graphically accomplished.

It will be remembered that logarithms are essentially exponents (to the base 10 in the common system), and that multiplication is accomplished by adding the logarithms. This is by the algebraic law

$$x^{m}x^{n} = x^{(m+n)} \text{..............} (6)$$

which may be verbally stated as follows: The multiplication of powers of the same quantity is effected by using the sum of the exponents as the exponent for the product.

Now, if the markings of the scales are not equidistant as in figure 18, *b*, but are laid off as



ALINEMENT DIAGRAM II, FOR COMPUTING THICKNESS.

in figure 18, *c*, so that the distances from the base are proportional to the logarithms of numbers, we can in effect add logarithms. But this is equivalent to multiplying the numbers. In the figure the multiplication of 4 and 5 is shown, the result being 20. In figure 18, *c*, the distance on the outer scales proportional to a logarithmic difference equal to 1 is 2 inches; on the middle scale it is half as great, or 1 inch.

The scales may be graduated in proportion to logarithms of trigonometric or other functions as well as in proportion to logarithms of numbers. It is therefore possible to manipulate a variety of factors.

Sometimes it is desirable to compress a scale, as for example a log. sin. scale in which the divisions between 1° and 20° come relatively far apart. In the charts here presented (Pls. XIV–XVI) the scales for logarithms of numbers were drawn with a modulus[1] of 10 inches. A log. sin. scale with a modulus of 10 inches would have to be 17.5 inches long in order to range from 1° to 90°. A log. tan. scale would have to be 35.2 inches long to range from 1° to 89°. When the moduli of the outer scales are not equal, the modulus of the middle scale is determined by the following formula, in which M_3 = modulus of middle scale, M_1 = modulus of right scale, and M_2 = modulus of left scale:

$$M_3 = \frac{M_1 M_2}{M_1 + M_2} \text{-------------} (7)$$

At the same time, the middle scale must be shifted toward that outer scale which has the smaller modulus. The position of the middle scale is determined by the following equation, in which M_1 and M_2 have the same values as before, D_1 = distance from middle scale to right scale, and D_2 = distance from middle scale to left scale.

$$\frac{D_1}{D_2} = \frac{M_1}{M_2} \text{--------------} (8)$$

The principles underlying this and the last equation may be deduced from figure 19. The principles of the diagram require that the middle scale must be so placed and have such a modulus that any two lines which intersect on one of the outer scales and cut off a distance on the middle scale equal to its modulus will also cut off a distance on the third scale equal to its modulus.

Let M_1, M_2, and M_3 be the moduli and D_1 and D_2 the distances of the outer scales from the middle scales. Assume the lettering as indicated.

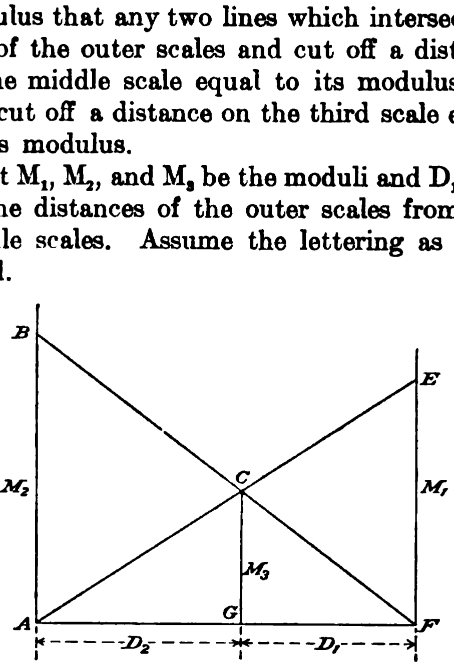


FIGURE 19.—Diagram for derivation of the interrelation of M_1, M_2, M_3, D_1, and D_2.

Then in the triangles ACG and AEF

$$\frac{M_3}{D_2} = \frac{M_1}{D_1 + D_2}$$

and

$$M_3(D_1 + D_2) = M_1 D_2$$

Similarly in the triangles FCG and FBA

$$\frac{M_3}{D_1} = \frac{M_2}{D_1 + D_2}$$

and

$$M_3(D_1 + D_2) = M_2 D_1$$

Therefore

$$M_2 D_1 = M_1 D_2$$

and

$$\frac{D_1}{D_2} = \frac{M_1}{M_2} \quad \text{(q. e. d.)}$$

Taking this proportion by composition and transposing, we have

$$\frac{M_1}{M_1 + M_2} = \frac{D_1}{D_1 + D_2}$$

Now, in the triangles FCG and FBA

$$\frac{M_3}{M_2} = \frac{D_1}{D_1 + D_2}$$

Substituting from the previous equation, we have

$$\frac{M_3}{M_2} = \frac{M_1}{M_1 + M_2}$$

---

[1] The term "modulus" is used to mean the length on a scale proportional to a unit difference of logarithms. For example, the outer scales in figure 18 are said to have a modulus of 2 inches because the distance from the point representing 1 to the point representing 10 is 2 inches. The logarithm of 1 is 0.000 and the logarithm of 10 is 1.000, and the difference between these logarithms is unity.

and solving for M_2, we have

$$M_3 = \frac{M_1M_2}{M_1+M_2} \quad \text{(q. e. d.)}$$

The length of any scale may be determined by the following equation:

$$L = M\ (\log F_1 - \log F_2) \ \ldots\ldots\ldots (9)$$

in which L = the length of the scale, M = its modulus, and F_1 and F_2 = the maximum and minimum values of the variable to be represented on the scale.

This may be explained by an example. Suppose it is desired to fit a log. tan. scale into a space about 12 inches long. Let $F_2 = \tan 1°$, and $F_1 = \tan 89°$. Then

$$\log F_2 = \log \tan 1° = 8.2419$$

$$\log F_1 = \log \tan 89° = 11.7581$$

then

$$\log F_1 - \log F_2 = 11.7581 - 8.2419 = 3.5162$$

and

$$L = M\ 3.5162$$

or

$$M = \frac{L}{3.5162}$$

Substitute 12 for L:

$$M = 12 \div 3.5162 = 3.41+$$

As an engineer's scale is used in drafting the scales and can be conveniently used only for moduli of 1, 1⅔, 2, 2.5, 3⅓, or 5 inches or these lengths multiplied by 10, we choose a modulus of 3⅓ inches, which is nearest to the inconvenient irrational decimal 3.41+. Substitute 3⅓ for M and we find $L = 3⅓ \times 3.5162 = 11.72$ inches.

ACCURACY AND ADVANTAGES.

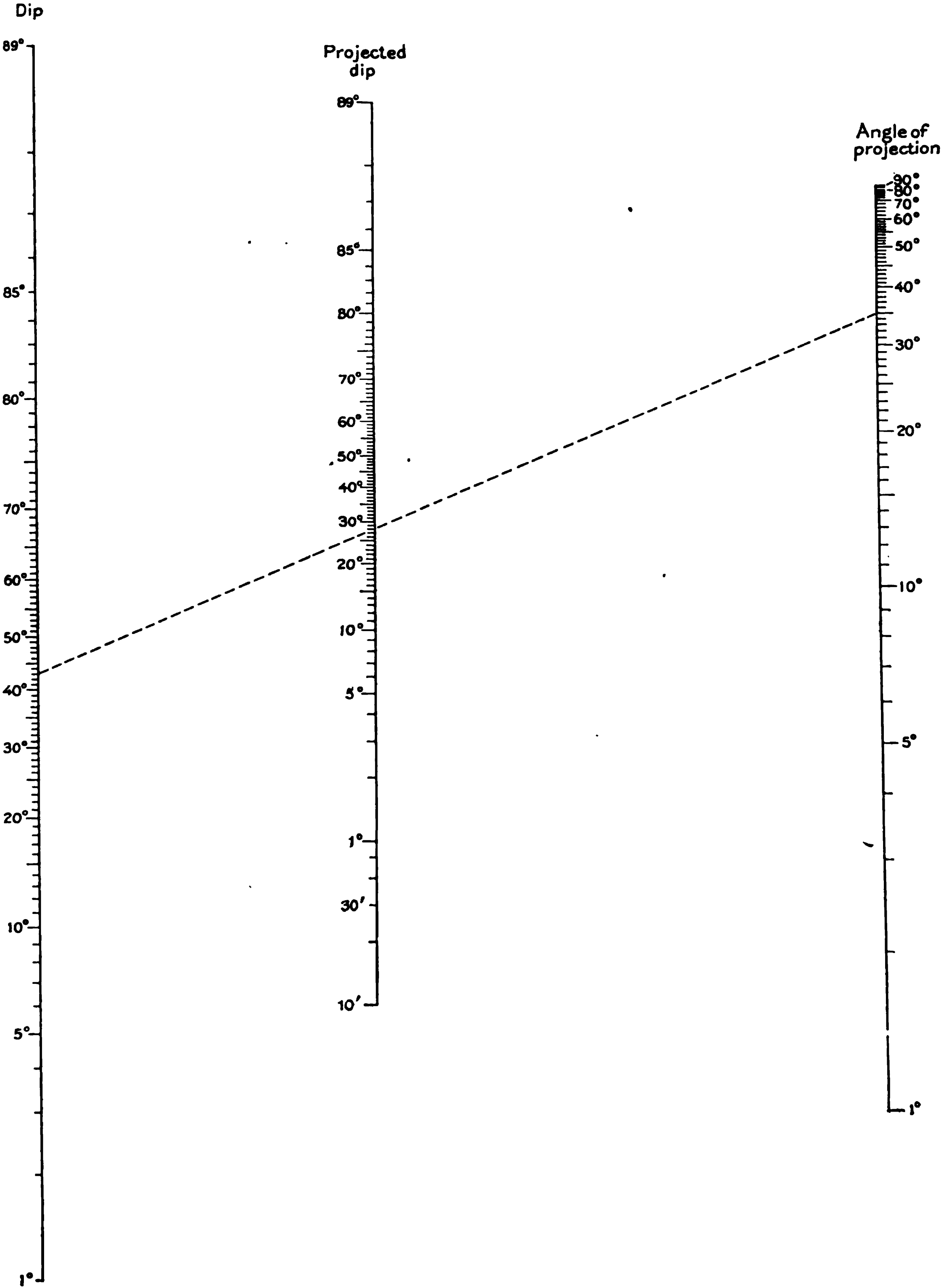
The point may be raised that the calculations made by these charts are not accurate, and in the strictest sense this is undoubtedly true. But there are two facts that should be borne in mind: (1) Measurements made by pacing or by a hand compass or clinometer are not accurate; (2) the surfaces with which the geologist deals are not true planes. Measurements of angles are seldom accurate within 1°, which is approximately equivalent to an error of 1 per cent, and pacing under the most favorable conditions can not be trusted closer than to 1 per cent. The undulations of fault or bedding planes will usually introduce an error of the same or greater magnitude. Therefore it is unsound logic to demand that the error in the calculations based upon such measurements be less than 1 per cent. If the chart is used with reasonable care, the error is somewhat less than 1 per cent and is therefore negligible. Moreover, the use of the chart gives less opportunity for the introduction of gross errors, such as come from a mistake in multiplication or in the addition of logarithms.

The charts, therefore, have the following advantages over the other methods for solving these equations:

1. They are more speedy. As a test of the speed of this method the writer used the first draft of the three charts for a series of test problems. The time required to solve the problems by means of the charts and by logarithms in the ordinary way was taken with a stop watch. It was found that the time with the charts ranged from one-sixth to one-fourth of that required by the logarithmic method. The test was fair to the logarithms, as the writer is reasonably proficient in their use.

2. The chances of gross errors are eliminated. In the test mentioned in the preceding paragraph the correctness of the answers was checked, and a mean error of about 0.2 per cent was found, with a maximum of 0.7 per cent. One gross error of about 40 per cent was made in one of the logarithmic solutions and was first detected by the check given by the chart solution.

3. It is unnecessary to keep the formula in mind, as it is incorporated in the construction of the chart.



ALINEMENT DIAGRAM III, FOR COMPUTING PROJECTED DIP.

A CONTRIBUTION TO THE GEOLOGY OF NORTHEASTERN TEXAS AND SOUTHERN OKLAHOMA.

By Lloyd William Stephenson.

PURPOSE AND SCOPE OF THE PAPER.

The region in central and northeastern Texas and southern Oklahoma known as the Black and Grand prairies abounds in features of interest to physiographers, geologists, and paleontologists, and the pioneer investigators of this region must have experienced renewed satisfaction in each day's exploration. The reports of Joseph A. Taff, Robert T. Hill, and others, published chiefly under the auspices of State and Federal surveys, represent with approximate accuracy at most places the general distribution of the outcrops of the formations in this region, and contain detailed descriptions of many sections that constitute a mine of useful information. The reader of the present paper is urged, therefore, to hold as most important the general excellence of the earlier reports of these authors and to relegate the inaccuracies and mistakes to which his attention will be called to the relatively unimportant place in which they belong, remembering at the same time that a future generation of investigators may find our own shortcomings as great as those we now criticize.

The present report treats of the area shown in Plate XVII, which includes Grayson, Fannin, Lamar, Delta, Hunt, and Collin counties, Tex., and the southern parts of Marshall and Bryan counties, Okla. It is based on the results of studies carried on during several brief field seasons between the years 1911 and 1917, inclusive. The results are by no means final, but enough facts have been obtained to justify their presentation to those who may be interested in the geology of the region. The purpose of the paper is therefore to set forth the present state of knowledge in the areal mapping, in the interpretation of structure, and in correlation, and to indicate certain mappable units and structural features that have not heretofore been recognized.

A comparison of Hill's geologic map published in 1901[1] with the map accompanying the present paper reveals at once certain inaccuracies in his representation of the areal distribution of the Cretaceous formations which require no further comment. Another striking feature of his map consists of the two great parallel faults, the Cook Springs and Red River (or Preston) faults, which are shown as extending from Love and Marshall counties, southern Oklahoma, far to the southeast through Grayson, Fannin, and other counties in Texas. Between the faults is an uplifted block represented as bringing to the surface formations that ought normally to be far below the surface. The reported existence of these faults, although unverified, has been cited in explanation of certain structural phenomena even as far east as northern Louisiana and Vicksburg, Miss.[2] The Cook Springs fault was first described by Taff[3] in 1893. In the light of the facts presented on subsequent pages the basis for the postulation of these faults in Texas disappears.

In 1902 Taff[4] indicated the geographic continuity of the Austin chalk and Annona chalk, which Hill failed to recognize, but he did not realize the magnitude of the upward transgression of the chalk across the geologic column from south to north and east. Gordon[5] in 1911 mapped with approximate accuracy the distribution east of the ninety-sixth meridian of the major lithologic units below the Eocene, to and including the Blossom sand, but he erred in correlating the Blossom sand with the Eagle Ford clay, and although he noted the geographic connection of the Annona chalk with the Austin he also failed to recognize the upward transgression of the chalk in its northeastward extension.

---

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[5] Gordon, C. H., Geology and underground waters of northeastern Texas: U. S. Geol. Survey Water-Supply Paper 276, pp. 21-25, pl. 1, 1911.

ACKNOWLEDGMENTS.

In 1911 the writer was accompanied by T. W. Stanton in a brief examination of parts of northeastern Texas, including the area in the longitude of Paris between the North Fork of Sulphur River and Red River, the vicinity of Cooper, Delta County, and the vicinity of Sherman, Grayson County. Subsequently he frequently conferred with Mr. Stanton in regard to the interpretation of the physical and paleontologic facts and has greatly benefited by his many helpful suggestions.

O. B. Hopkins, during a brief visit in 1915, determined the stratigraphic succession and attitude of the Upper Cretaceous rocks that appear at the surface in the vicinity of Wolfe City, Hunt County, and Gober, Fannin County, Tex. He stated his conclusions to the writer and indicated certain favorable localities for examining outcrops. The area was subsequently visited by the writer, who traced the several lithologic divisions both to the northeast and southwest of Wolfe City, as shown on Plate XVII. Mr. Hopkins also obtained by correspondence the logs of several wells in northeastern Texas and southern Oklahoma, which he generously placed at the writer's disposal.

In December, 1917, O. B. Hopkins and Sidney Powers accompanied the writer in a supplementary field study of the areas in Grayson, Fannin, and Hunt counties where the Cretaceous formations are involved in the Preston anticline and in the Leonard-Celeste monoclinal nose. The outcrops of key rocks were traced, and altitudes were determined at numerous points on them by means of aneroid readings. Messrs. Hopkins and Powers continued the determination of altitudes during the later part of December and the first half of January, 1918. H. M. Robinson had in 1917 made a series of similar altitude determinations on a part of the Preston uplift in southern Marshall County, Okla., locally known as the Enos anticline. The general results obtained by these three men are embodied in the structure contours shown as an overprint in red on the geologic map (Pl. XVII). A more detailed report of their results, with particular reference to the occurrence of oil and gas, will be published later as an economic bulletin.

Indebtedness is gratefully acknowledged to Mr. J. T. Bryant, of Pottsboro, Tex., for information and personal assistance that enabled the writer and his associates quickly and advantageously to find and study numerous important exposures in northern Grayson County, Tex., and southern Marshall County, Okla. Mr. Bryant also kindly contributed the logs of several wells on the Preston anticline.

Courtesies were also extended to the writer and to his associates by Messrs. R. H. Cook, of Denison; M. L. Wilson, of Wolfe City; and J. Balch Moor, of Bonham, who furnished well logs and placed facilities for field study at their disposal.

LITERATURE.

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Taff, J. A., U. S. Geol. Survey Geol. Atlas, Atoka folic (No. 79), 8 pp., 4 maps, 2 columnar-section sheets, 1902.

Taff, J. A., U. S. Geol. Survey Geol. Atlas, Tishomingo folio (No. 98), 8 pp., 3 maps, 1 columnar-section sheet, 1903.

EXPLANATION

TERTIARY

▨ Te

Midway formation and part of the Wilcox formation

(Sand and clay)

UNCONFORMITY

CRETACEOUS

▨

Navarro formation

(Calcareous clay and sand)

▨

Taylor marl

(Calcareous shaly clay)

Pecan Gap chalk member, Ktp

Wolfe City sand member, Ktw

▨

Austin chalk

Includes Ector tongue (a *on map*) *and Annona tongue* (b *on map*). *Includes also, for convenience of mapping, 10 to 35 feet of unnamed nonchalky clay and sand, down to and including the "fish-bed conglomerate")*

▨ **Clay eqvivalent to part of Austin chalk on the west, and in part to the Blossom sand and Brownstown marl on the east**

▨

Brownstown marl

(Calcareous clay)

▨ Kbl

Blossom sand

(Calcareous glauconitic sand)

▨

Eagle Ford clay

(Dark shaly clay)

▨ Kw

Woodbine sand

(Fine to coarse sand and clay)

UNCONFORMITY ?

▨

Washita group

(Includes in ascending order Kiamichi clay, Duck Creek formation, Fort Worth limestone, and Denison for-

Veatch, A. C., Geology and underground-water resources of northern Louisiana and southern Arkansas: U. S. Geol. Survey Prof. Paper 46, 422 pp., 51 pls., 1906.

Gordon, C. H., The chalk formations of northern Texas: Am. Jour. Sci., 4th ser., vol. 27, pp. 369–373, 1909.

Taff, J. A., and Reed, W. J., The Madill oil pool, Okla.: U. S. Geol. Survey Bull. 381, pp. 504–513, 1910.

Gordon, C. H., Geology and underground waters of northeastern Texas: U. S. Geol. Survey Water-Supply Paper 276, 78 pp., 2 pls., 1911.

Shannon, C. W., and others, Petroleum and natural gas in Oklahoma: Oklahoma Geol. Survey Bull. 19, pt. 2, pp. 316–321, 1917.

TOPOGRAPHY AND DRAINAGE.

The area shown on Plate XVII lies near the northwestern border of the Gulf Coastal Plain in northeastern Texas and southern Oklahoma, and is a dissected coastal-plain upland ranging in altitude from about 530 feet in the southeast to 850 feet in places in the northwest. The highest points in the area are between Denison and Pottsboro, Grayson County, Tex., where several hills rise slightly more than 900 feet above sea level. Red River, which crosses the area from west to east in a sinuous course near the northern margin, has cut a broad valley 200 to 300 feet below the general upland, the altitude of low-water level where the river enters the area being approximately 590 feet and where it leaves the area not quite 400 feet. A little less than the northern half of the area is drained by tributaries of Red River. In the east, south of the Red River valley, the drainage is carried by tributaries of Sulphur River, which flows eastward and joins Red River in Louisiana. The southern and southwestern parts of the area are drained by numerous southward-flowing creeks belonging to the Trinity River system.

The drainageways of the area present many good examples of consequent, subsequent, obsequent, and perhaps other classes of streams, a detailed description of which is outside the scope of this paper. Attention may be called, however, to the conspicuous development of small tributaries of South Sulphur River, itself a subsequent stream, which flow down the gentle southward-facing slope of the cuesta formed by the Pecan Gap chalk in Delta County and the northeastern part of Hunt County, and the similar tributaries of North Sulphur River, also a subsequent stream, which flow southward on the corresponding slope of the cuesta formed by the Annona tongue of the Austin chalk in southern Lamar and Fannin counties. (See p. 132 and Pl. XVII.) These are not consequent streams, as that term was originally defined, in that their courses are not determined in consequence of the original slope produced by the uplift of the area from beneath the sea, but rather in consequence of the southward slope of the chalk and clay formations down whose eroded surfaces they flow. With the exception of some of the smaller streams in the terraced area along Red River the drainage is almost completely adjusted to the structure of the underlying Cretaceous formations, and in general the area affords an excellent example of maturely adjusted drainage on only partly consolidated, unequally resistant rocks of gentle monoclinal attitude.

The area falls chiefly within the four physiographic divisions[1] commonly known as the Black Prairies, the Eastern Cross Timbers, the Grand Prairies, and the Western Cross Timbers. The boundaries separating these divisions are approximately coincident with the boundaries of underlying formations composed of unequally resistant rocks, but these boundaries are not everywhere sharply defined. Along Red River is a belt of alluvial terrace plains of Pleistocene age (see p. 132), which ranges in width from 2 or 3 miles where the river enters the area, at the west, to 15 miles or more in the northeastern part of the area and which may well be classed as a physiographic division distinct from each of the four just enumerated.

The Black Prairies embrace chiefly the areas in Collin, Hunt, Delta, Lamar, Fannin, and Grayson counties underlain by the marine chalks, clays, and marls of the Gulf series. (See geologic map, Pl. XVII.) Topographically these areas are characterized in the main by nearly level to gently rolling surfaces, merging near Red River and the larger creeks into hills of moderate relief and smoothly rounded slopes. Cuestas of low relief have been produced by the relatively resistant chalk members of the series as described on a subsequent page.

The Eastern Cross Timbers include the relatively narrow belt underlain by the Woodbine sand of the Gulf series (see Pl. XVII), which extends from the northwestern part of

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[1] Hill, R. T., U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, pp. 65–75, pl. 10, 1901.

Fannin County west by north through Grayson County to the vicinity of Gordonville and thence south along the western border of the area mapped. The belt is characterized by sandy hills of pronounced relief, supporting a growth of blackjack and post oak trees; a good example is afforded by the hills within several miles southwest and west of Denison, Grayson County. (See Pl. XXVI.) As shown elsewhere in this report, however, the Woodbine formation is irregularly bedded, and locally considerable parts of it are composed of clay which has produced a gently rolling surface similar to that of the Black Prairies; such an area occurs along the central and southern parts of the belt of outcrop of this formation for a distance of several miles west-northwest from Pottsboro, Grayson County.

The Grand Prairies include the area along the south limb of the Preston anticline in northern Grayson County, Tex., and small areas along the north limb of the anticline in Marshall County, Okla., underlain by the limestones and shaly clays and marls of the Comanche series down to but not including the Trinity sand. (See geologic map, Pl. XVII.) This belt resembles the Black Prairies in its gently rolling to moderately hilly aspect, but the indurated layers of the Comanche series, including in ascending order those of the Goodland, Duck Creek, Fort Worth, "Quarry," and Main Street limestones, tend to produce numerous small benches and low cuestas in the otherwise smooth to moderately rolling surface; these features are well exhibited in Grayson County in the northward-facing slope of the Red River valley, north of the belt of outcrop of the Woodbine sand. The belt of outcrop of the sandy strata of the Pawpaw member locally produces a narrow belt of timbered, sandy soil within the Grand Prairies, which resembles the Eastern Cross Timbers.

The Western Cross Timbers are represented in this area chiefly by a narrow belt that marks the crest of the Preston anticline in southern Marshall County, Okla., west of Preston Bend of Red River, where the sandy strata of the Trinity sand come to the surface. Topographically the area is hilly and similar to that of the Eastern Cross Timbers.

The belt of alluvial terrace plains bordering Red River includes plains at several levels: (1) The present flood plain of Red River is narrow along that part of the river bordering Grayson County, Tex., but broadens out to 3 or 4 miles in places along the northern border of Fannin and Lamar counties, Tex., and the southern border of Bryan County, Okla. (2) A well-defined river terrace 45 to 75 feet above low-water level of Red River is moderately extensive in places along the river valley; the village of Preston, in Preston Bend, in the northern part of Grayson County, is situated on an exceedingly flat portion of this plain, 4 or 5 square miles in extent, and Woodville, about 2½ miles north of Preston, in Marshall County, Okla., stands on a somewhat larger portion of the plain. (3) A terrace plain 140 to 160 feet above water level is represented here and there in that part of the valley above the mouth of Washita River but occupies extensive areas in the valley below that river; in the southwestern part of Bryan County, Okla., the alluvial deposits of this terrace form a flat sandy plain 8 miles or more in width from north to south, and large areas of the plain occur in the northern parts of Fannin and Lamar counties, Tex. (4) Remnants of surficial deposits were observed at still higher altitudes at several places in the area and may represent one or more additional terraces. The alluvial deposits on these terrace plains effectually obscure the Cretaceous formations over many square miles in the Red River valley, rendering it difficult to determine the areal extent and structure of the formations.

Minor features of the topography that have an important bearing on the areal mapping and the determination of the stratigraphy and structure are the ridges, benches, and stream bluffs produced by the more resistant strata of both the Comanche and Gulf series. Many of these features take the form of cuestas—that is, broad, low ridges of great linear extent that trend parallel to the strike of the rocks and present long, gentle slopes to the east, southeast, or south in the direction of the dip and short, steep slopes on the inland side, which marks the western edge of the outcrop of the harder ridge-forming strata. An example is the white rock escarpment of Hill,[1] which marks the western and northern edge of the Austin chalk in Grayson and Collin counties and which makes a relatively steep descent from a portion of the Coastal Plain upland that is underlain by the Austin chalk to a belt of the upland that lies 75 to 100 feet or more lower and is underlain by the softer Eagle Ford clay. Similar examples are the relatively steep slopes that mark the northern edges of the Annona tongue of the Austin chalk in Fannin and Lamar counties and of the Pecan Gap chalk in Delta, Fannin, Hunt, and Collin counties. (See geologic map, Pl. XVII.)

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[1] Hill, R. T., U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, p. 68, 1901.

GENERAL GEOLOGIC FEATURES.

The area shown on the geologic map (Pl. XVII) is underlain throughout its extent by strata of Cretaceous age, which rest upon a buried, moderately smooth basement composed of ancient rocks. Just to the north, in the Atoka and Tishomingo quadrangles, Okla., where the basement comes to the surface, it includes Paleozoic sedimentary rocks of Cambrian, Silurian, Devonian, and Carboniferous age and pre-Paleozoic granites. The upper surface of the basement rocks is believed to be a peneplain formed by erosion prior to the deposition of the Cretaceous sediments upon it and subsequently tilted slightly coastward.

The northern boundary of the Cretaceous deposits trends about due west 10 to 30 miles north of Red River, and the western boundary trends south by west through Montague, Wise, and Parker counties, Tex. Both these boundaries are outside the area shown on Plate XVII. The tilted peneplained surface of the basement rocks dips to the south from the northern boundary at rates estimated to range in different places from 50 to 70 feet or more to the mile, and to the southeast from the western boundary at rates probably ranging from 40 to 50 feet to the mile. Within the area mapped the basement rocks lie nearest to the surface beneath the crest of the Preston anticline, in the southern part of Marshall County, Okla., and the northern part of Grayson County, Tex., where their depth ranges from 350 to 700 feet; they lie deepest in the southeastern part of the area, where their depth is estimated as between 4,000 and 5,000 feet.

The basement rocks are separated from the overlying Cretaceous deposits by an unconformity representing a long interval of geologic time, including at least the Triassic and Jurassic periods and probably a considerable part of the Lower Cretaceous epoch.

The Cretaceous deposits are divisible into two great series, a lower, the Comanche series, which appears at the surface about the flanks of the Preston anticline in the northwestern part of the area and has an estimated thickness of 800 to 1,000 feet, and an upper, the Gulf series, which has an estimated thickness of at least 3,000 feet and the outcrop of which covers considerably more than half the area. Each of these series is separable into subordinate divisions, which are discussed on subsequent pages. The Gulf series is unconformably overlain by strata of Eocene age which appear at the southeast in a relatively small part of the area under discussion. (See Pl. XVII.) In general the strike of the strata is parallel to the inner margin of the Coastal Plain, and the dip is coastward from this margin at rates ranging from 30 feet or less to 80 feet or more to the mile. A considerable departure from the prevailing regularity in strike and dip occurs in the northwestern and central parts of the area, in connection with the Preston anticline, described on pages 159, 160. A less pronounced departure from the common monoclinal structure is occasioned by the fold which produced the Leonard-Celeste monoclinal nose, described on page 161.

The Cretaceous deposits consist of sand, shaly clay, calcareous shaly clay, limestone, and chalk. With the exception of the Trinity sand (p. 134) and the Woodbine sand (p. 145), both of which were laid down in deltas and in marginal marine waters, all these deposits are of typical marine origin.

The boundaries of the formations as indicated on Plate XVII are in part very much generalized. Where they are established with approximate accuracy for the scale of the map by the personal observations of the writer and his associates or by published evidence regarded as sufficiently reliable, the boundaries are drawn as full lines. Elsewhere the boundaries have been determined by general considerations or by using the unverified boundaries indicated on maps of Hill, Taff, and Gordon and are drawn as broken lines. The geologic formations of the northeastern part of Fannin County and the northern part of Lamar County are little known, owing in part to an extensive covering of Pleistocene alluvial terrace deposits which largely conceal the Cretaceous formations in a broad area bordering

Red River on the south, and in part to the inadequacy of the field work that has been done in the area. The writer has not examined the boundary between the Woodbine and Eagle Ford formations anywhere in western Grayson and eastern Denton counties, nor the boundary between the Eagle Ford and Austin south of the Texas Pacific Railroad in Grayson and Collin counties. The position assigned to the Cretaceous-Eocene contact in Hunt and Hopkins counties is based chiefly on the maps of Hill and Gordon.

CRETACEOUS SYSTEM.

COMANCHE SERIES.

GENERAL CHARACTER.

The Comanche series consists of sands, shaly clays, marls, and limestones having an estimated thickness in northeastern Texas of 800 to 1,000 feet. The series has been subdivided in Texas in ascending order into the Trinity, Fredericksburg, and Washita groups, all of which are represented in the area treated in this paper. (See Pl. XVII.) In this area the series appears in surface exposures only in the northern part of Grayson County, Tex., and in an adjacent area north of Red River in the southern parts of Marshall and Bryan counties, Okla., where it has been brought to the surface by the uplift that produced the Preston anticline. (See p. 159.) Were it not for this anticline the series would lie buried beneath the Gulf series in the area mapped, with the possible exception of its extreme northwestern corner. Hill's classification of the Comanche series in Grayson County is given in column C in Plate XVIII.

The Comanche series is of Cretaceous age. Until recently the series has been regarded by American geologists as belonging to the Lower Cretaceous, but for a number of years certain European geologists, notably Douvillé,[1] have regarded the series as in part Upper Cretaceous. Berry and Knowlton[2] now correlate the Washita, the uppermost group of the series, unquestionably with the Cenomanian (Upper Cretaceous). Whatever may be the position of this series with respect to the standard European section, it is reasonably certain that the Comanche constitutes a closely related lithologic and paleontologic series.

TRINITY SAND.

The Trinity group, which is represented in northeastern Texas chiefly by sand (the "Antlers sand" of Hill), is the basal division of the Comanche series. According to well records this sand is 400 to 700 feet thick in the vicinity of Red River in Grayson County, Tex., and Marshall County, Okla. Taff, who studied it in the Tishomingo quadrangle, Okla., a few miles north of Grayson County, states that the formation consists of fine, compact incoherent sand and scattered lentils of sandy clay, with a basal conglomerate a few feet to 50 feet thick, which in the western half of the quadrangle is cemented with chalky white lime.[3] Pebbly lenses occur in the sand in places.

In the area under consideration the sand is at the surface in the axial portion of the Preston anticline, in an irregular belt having a maximum width of 7 or 8 miles, extending from a point several miles southeast of Rock Bluff, on Red River, to the northwest corner of the area in Oklahoma, as shown on the geologic map (Pl. XVII). Localities where the sand was examined are mentioned or briefly described below.

At Rock Bluff, Red River, 2½ miles south of Preston or 8½ miles northwest of Denison, Grayson County, Tex. (see Pl. XIX, *A*), near the axis of the Preston anticline, the upper 150 feet of the Trinity is well exposed, as described in the following section:

Section at Rock Bluff, Red River, Grayson County, Tex.

[Altitude at top of section estimated to be 690 feet above sea level.]

		Feet.
Fredericksburg group (Goodland limestone):		
Hard massive limestone		10
Shaly clay, poorly exposed	Walnut shaly member	1
Limestone		2
Trinity sand ("Antlers sand" of Hill):		
Light-gray, mostly fine argillaceous irregularly bedded compact sand, with subordinate lenses of fine sandy clay and some pebbly lenses; in the lower 30 feet are interbedded lenses of purplish clay having a maximum observed thickness of 6 feet		150
		163

In a bluff of Red River 1½ miles above Rock Bluff, 1¼ miles south by east of Preston, 30 feet

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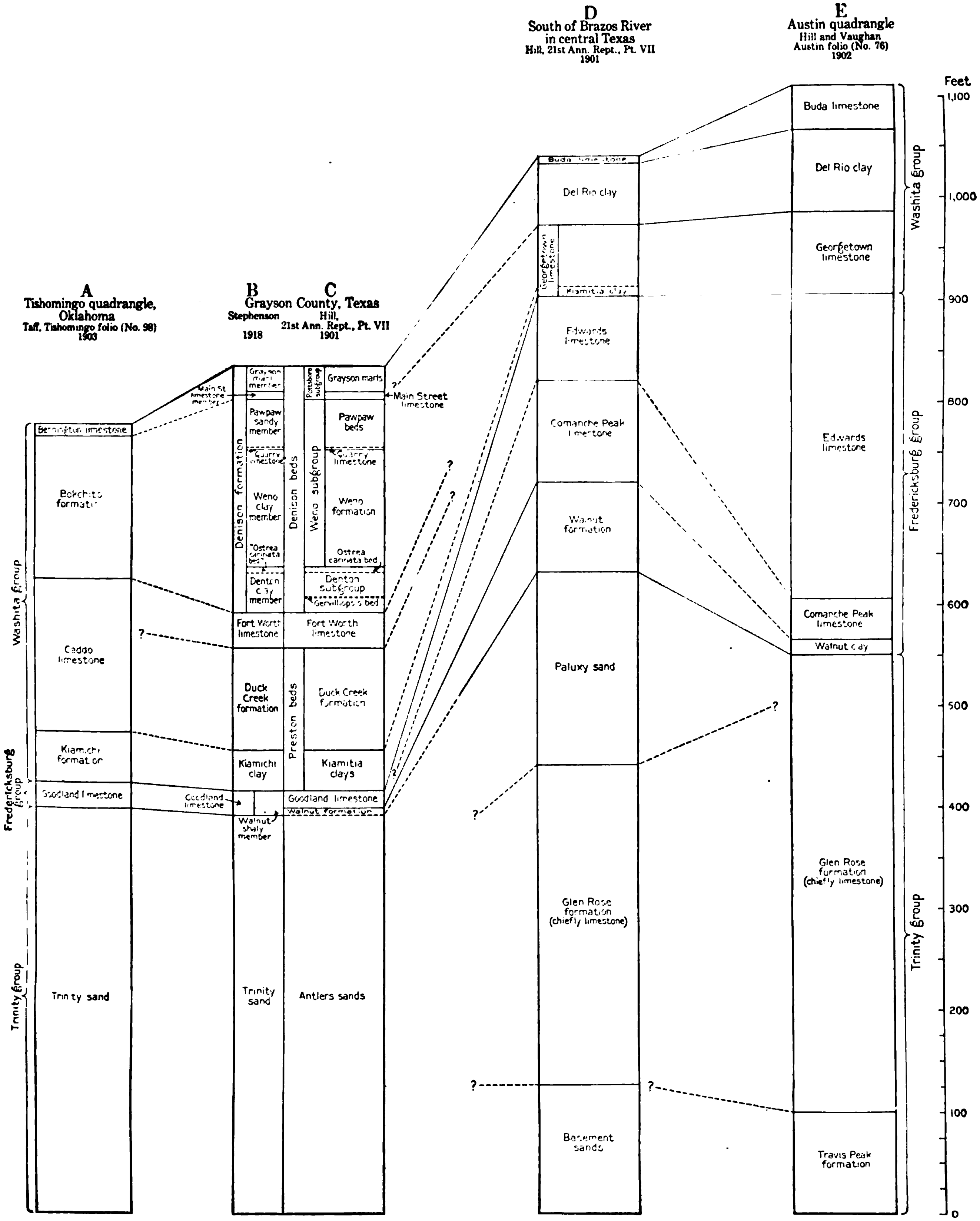
[1] Douvillé, H., Sur quelques rudistes américains: Soc. géol. France Bull., 3d ser., vol. 28, p. 218, 1900.

[2] Berry, E. W., The Upper Cretaceous floras of the world: Maryland Geol. Survey, Upper Cretaceous, pp. 222, 223, 1916.

[3] Taff, J. A., U. S. Geol. Survey Geol. Atlas, Tishomingo folio (No. 98), p. 6, 1903.



CORRELATION TABLE SHOWING THE RELATION OF THE SUBDIVISIONS OF THE COMANCHE SERIES IN GRAYSON COUNTY, TEX., TO THE FORMATIONS OF THE SAME SERIES IN OTHER PARTS OF TEXAS AND OKLAHOMA.

of Trinity sand essentially like that just described is exposed beneath 30 feet of Pleistocene terrace alluvium.

In the public road 1½ miles west of Preston 30 or 35 feet of Trinity sand outcrops in the steep westward-facing slope of the Red River valley, and the Goodland limestone forms a ledge at the crest of the hill, about 650 feet above sea level. Pebbly lenses were noted in the Trinity at this locality.

At Henderson Ferry on Red River, 4 miles west by south of Rock Bluff, the upper 40 feet of the Trinity is moderately well exposed and consists of fine to coarse gray and yellow sand with small mechanically included fragments of clay and slightly indurated sand. The sand is overlain by the Goodland limestone, including the Walnut member at its base, which is poorly exposed.

Good exposures of the Trinity occur in the southern part of Marshall County, Okla., on the headwater branches of Sand Creek, 6 miles south by west of Kingston; in the valley of Buncombe Creek, 2½ to 8 miles north by east of Willis Ferry; and in the valleys of Brier and House creeks, 3 to 8 miles north and northwest of Willis Ferry.

The northwesternmost locality where the Trinity was examined by the writer is on the northeastward-facing slope of the Red River valley about a mile southeast of Orlena, in the extreme northwestern part of Grayson County, Tex. Here the Goodland limestone caps the hill, forming a rocky ledge at its crest at an altitude of about 750 feet, and 75 feet or more of the Trinity appears in the steep slope below the Goodland.

South of the Red River region in Texas the middle portion of the Trinity becomes calcareous, and south of Brazos River is separable according to Hill[1] in ascending order into the basement sands, 127 feet; the Glen Rose formation, chiefly limestone, 315 feet; and the Paluxy sand, 190 feet. Still farther south, at Austin, the Paluxy sand is apparently represented by limestone in the upper part of the Glen Rose, so that the Trinity is separable in ascending order into only two parts—the Travis Peak formation, consisting of conglomerate, grit, sand, clay, and calcareous beds, 100 feet; and the Glen Rose formation, chiefly limestone, 450 feet. (See Pl. XVIII.)

FREDERICKSBURG GROUP.

GOODLAND LIMESTONE (INCLUDING WALNUT SHALY MEMBER).

The Trinity sand is overlain by the Fredericksburg group, which in northeastern Texas is represented by the Goodland limestone, only 13 to 20 feet thick. The Goodland outcrops in a narrow area on the flanks of the Preston anticline, surrounding the area of outcrop of the Trinity sand (see Pl. XVII), in northern Grayson County, Tex., and in southern Marshall and Bryan counties, Okla. Along the south side of the anticline the Goodland dips south by west at rates ranging from 40 to 300 feet or more to the mile. The steepest known dip occurs about a mile and a half northeast of Pottsboro. (See structure contours, Pl. XVII.)

The basal 3 to 6 feet of the Goodland limestone consists of layers of persistent hard thin-bedded coquina-like limestone with interbedded thin layers of dark marly shale, which are in this paper called the Walnut shaly member. These beds were not recognized by Hill[2] in the type section at Goodland, in Choctaw County, Okla. He says:

> Proceeding westward along the ancient Ouachita shore line from Arkansas into Texas, the *Exogyra texana* beds (the Walnut clays and *Gryphaea* breccia) are missing until the escarpment is reached north of Marietta, in the Chickasaw Nation [Love County, Okla.], where they first appear, thinly represented beneath the Goodland limestone.

In 1894[3] and again in 1901[4] Hill restricted the term "Goodland" to the massive limestone between the underlying Walnut clay, which he regarded as forming the upper part of the "Antlers" (Trinity) sand, and the overlying Kiamichi clay. In the Atoka folio[5] and again in the Tishomingo folio,[6] Taff included the Walnut clay in the Goodland, and this usage has subsequently been followed by Taff and other authors. Although the United States Geological Survey has adopted Taff's usage of Goodland, the present writer is of the opinion that future investigations will demonstrate the appropriateness of restricting the application of the name to the massive limestone above the interbedded shaly clay and coquina-like limestone, here called Walnut shaly member, in accordance with Hill's original usage.

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[1] Hill, R. T., U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, pp. 153-154, 171, 1901.

[2] Geol. Soc. America Bull., vol. 2, pp. 502-514, 1891.

[3] Geol. Soc. America Bull., vol. 5, pp. 303, 304, 1894.

[4] U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, pp. 216-222, 1901.

[5] U. S. Geol. Survey Geol. Atlas, Atoka folio (No. 79), 1902.

[6] Idem, Tishomingo folio (No. 98), 1903.

Southward from Grayson and Cooke counties in Texas the Walnut member becomes thicker, and in Tarrant and Johnson counties it assumes the importance of a formation rather than a member; here it consists of alternating hard and soft thin-bedded limestone and marl and reaches a maximum thickness of 140 or 150 feet. Still farther south, in Hood and Somervell counties, the thickness again decreases to approximately 90 feet, and in the vicinity of Austin, Travis County, it is only 15 feet. (See Pl. XVIII.) The type locality of the Walnut member is at Walnut (or Walnut Springs), in Bosque County.

Above the Walnut member the Goodland consists of 10 to 15 feet of hard massive persistent limestone, which weathers white. This limestone forms conspicuous outcrops and is therefore a valuable key rock in determining structure from surface exposures. It is easily recognizable in well borings, its position so closely above the Trinity sand preventing its confusion with other limestones in the overlying Washita group. As a rule, the drillers do not differentiate the few feet of limestone and marl of the Walnut member at the base of the Goodland limestone. Characteristic fossils of the Goodland limestone are *Gryphaea marcoui* Hill and Vaughan, *Exogyra texana* Roemer, *Remondia robbinsi* (White), *Cerithium bosquense* Shumard, and *Schloenbachia acutocarinata* (Shumard). The importance of the Goodland as a key rock warrants a fairly full description of its occurrence about the flanks of the Preston anticline.

One of the easternmost outcrops of the Goodland near the crest of the Preston anticline is in the banks of a small creek entering Shawnee Creek just below the pumping station at the city lake, 4 miles northwest of Denison. The creek near its mouth is intrenched in the limestone to a depth of 6 to 7 feet, and the limestone is overlain by a few feet of alluvium. Upstream the top of the limestone gradually becomes lower with respect to water level, and within a few hundred yards it passes beneath the bed of the creek. At Bears Ferry, Red River, 1½ miles north by east of the city lake, the top of the Kiamichi formation is about 25 feet above water level, showing that the Goodland is here 15 or 20 feet below water level. Within a mile west of Bears Ferry the Goodland rises above water level and forms a gradually rising ledge in the northward-facing slope of the Red River valley westward to Rock Bluff, where the base of the limestone lies a little more than 150 feet above the river. The section at Rock Bluff is described on page 134.

West of Rock Bluff the Goodland appears in both slopes of the Little Mineral Creek valley, but its southward dip carries it below the surface in the bed of the creek at a point approximately 4¼ miles north of Pottsboro. A fine exposure of the limestone is afforded by a bluff on this creek 4½ miles north of Pottsboro. (See Pl. XIX, *B*.)

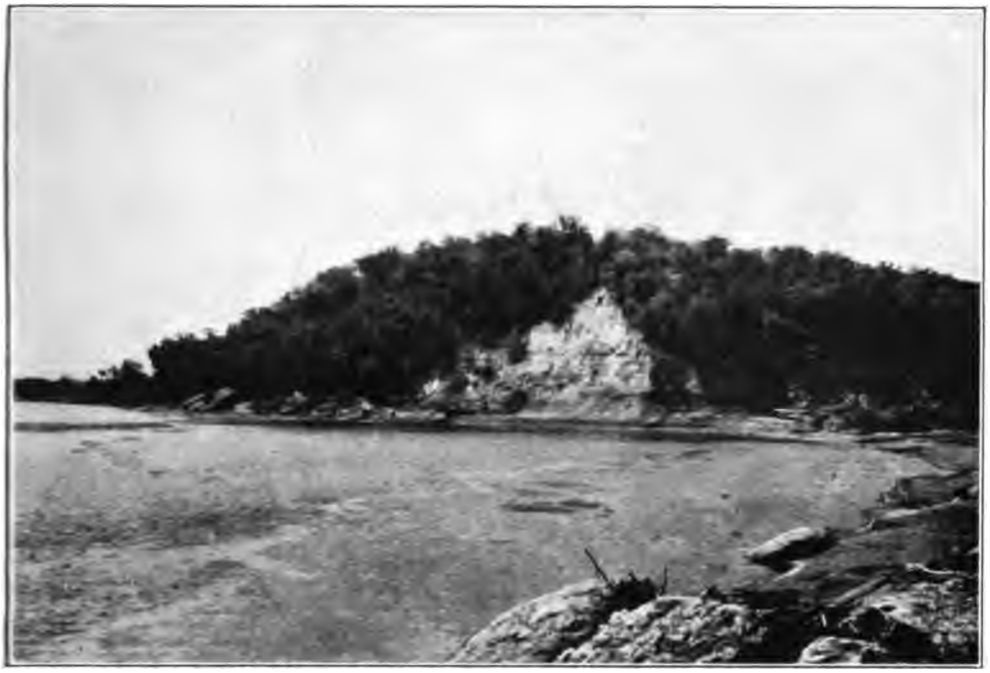
Section on Little Mineral Creek 4½ miles north of Pottsboro, Grayson County, Tex.

[Altitude at top of section estimated to be 615 feet above sea level.]

	Feet.
Soil	2
Fredericksburg group (Goodland limestone):	
Massive limestone	13
Walnut shaly member: Hard thin-bedded coquina-like limestone containing *Ostrea subovata* Shumard, *Gryphaea marcoui* Hill and Vaughan, *Trigonia* sp., and *Anomia* sp., with interbedded thin layers of dark marly shale	6
	21

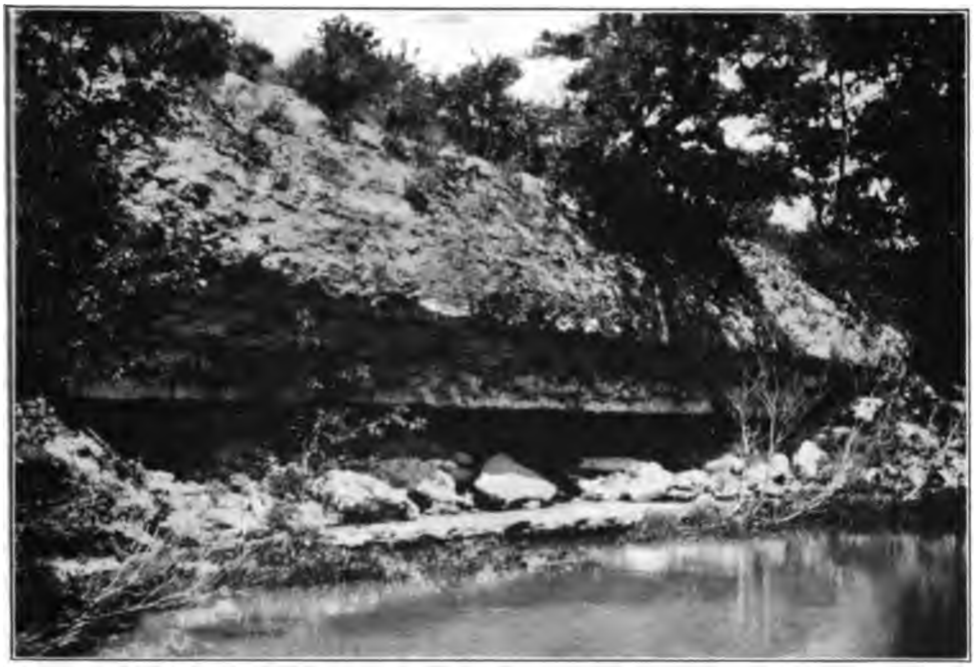
Both the massive limestone and the underlying Walnut shaly member are well exposed in a branch in the eastward-facing slope of Little Mineral Creek, 6 miles north of Pottsboro (3 miles north of Fink), where a thin earthy calcareous layer in which cone-in-cone structure was well developed was noted about a foot below the top of the Walnut member. On the divide between Little Mineral Creek and Red River the Goodland extends northward to a point 7 miles north of Pottsboro, where the altitude of its top is about 720 feet above sea level. The limestone here lacks less than 2 miles of closing to the north over the crest of the Preston anticline, its absence in this interval being due to erosion which has removed the Goodland from the underlying Trinity. (See p. 137 and Pl. XVII.)

At Henderson Ferry, Red River, 6¾ miles north by west of Pottsboro, the base of the Goodland is only 35 or 40 feet above water level, and upstream from the ferry, within an estimated distance of 1 or 2 miles, it finally comes down to water level and crosses into Oklahoma beneath the Pleistocene and Recent alluvial deposits of the Red River valley.



A. TRINITY SAND AND LOOSE SLABS OF GOODLAND LIMESTONE AT ROCK BLUFF (OLD MARSHALL BLUFF) ON RED RIVER, 8½ MILES NORTHWEST OF DENISON, GRAYSON COUNTY, TEX.

The upper 150 feet of the Trinity is exposed in the bluff. The Goodland limestone, which immediately overlies the Trinity, forms a ledge along the crest of the bluff, and large masses of rocks broken from it have fallen down the slope, giving rise to the name Rock Bluff.



B. GOODLAND LIMESTONE ON LITTLE MINERAL CREEK IN NORTHERN GRAYSON COUNTY, TEX.

The massive Goodland limestone is underlain by the Walnut shaly member (the undermined portion).

Northwest of Henderson Ferry, in Marshall County, the southward-dipping limestone appears in the valley slopes of the southward-flowing creeks tributary to Red River and was especially noted along two small creeks respectively 3 and 3½ miles east of Willis Ferry. North of Willis Ferry the Goodland crops out in both the east and west slopes of the ridge separating Buncombe and Brier creeks, and its continuity is interrupted at only one place on the crest of the ridge, where it has been eroded away. At a point estimated to be about 3½ miles west by north of Willis Ferry the Goodland again crosses Red River into Grayson County, Tex., where, gradually rising to the northwest in the northeastward-facing slope of the river valley, it finally forms the crest of the hill overlooking the valley about a mile southeast of Orlena. The Trinity sand appears in the slopes of this hill below the Goodland.

On the north limb of the Preston anticline the Goodland crops out in the valley of Rock Creek south of Kingston, in Marshall County, Okla., and is especially well exposed in a branch about 3¾ miles south by west of Kingston. The section here shows the upper massive limestone, underlain by the Walnut shaly member, and this in turn by the Trinity sand. Down the valley of Rock Creek from this locality the limestone appears in the southwestward-facing slope, gradually descending toward water level until, in the vicinity of the big bend a mile or two west of Woodville, it crosses the Red River valley beneath the Pleistocene and Recent alluvial deposits and reappears on the Texas side of the river in the hills in the northern part of Preston Bend, Grayson County. A good exposure of the limestone was noted in the public road on the westward-facing slope of the Red River valley 1½ miles west of Preston, where it is underlain by 30 or 35 feet of Trinity sand that outcrops in the slope below the limestone. This locality is less than 2 miles north of the northernmost occurrence of the limestone in the south limb of the anticline on the divide between Little Mineral Creek and Red River. (See p. 136.) The limestone here and in other outcrops in this vicinity dips to the northeast at an angle sufficient to carry it 40 or 50 feet below water level at Thomson Ferry, a mile north of Preston, Tex.

East of Preston the Goodland again crosses the Red River valley beneath alluvial deposits, and although not traced in detail it was examined in an outcrop at the foot of a terrace scarp at the edge of the Red River bottom about half a mile north of Bears Ferry, in Bryan County, Okla. Here the top of the limestone is 30 or 35 feet above water level.

South of Red River in Cooke County, Tex., the Goodland gradually increases in thickness. It is regarded as the time equivalent of the Walnut clay, and of the Comanche Peak and Edwards limestones of central Texas, which south of the Brazos River valley have a combined thickness of over 250 feet; still farther south the Edwards continues to thicken, being 300 feet thick in the vicinity of Austin, Travis County (see Pl. XVIII), and 520 feet thick in Uvalde County, whereas the Walnut and Comanche Peak become thinner, the former being only 15 feet and the latter 40 feet thick in the vicinity of Austin.

WASHITA GROUP.

LITHOLOGY AND SUBDIVISIONS.

The Washita group consists chiefly of marine shaly clay, marl, and interbedded subordinate limestone, having a total estimated thickness in northern Grayson County of 415 feet; toward the top there is a sandy member, the Pawpaw (see p. 142), which is the only conspicuous exception to the nonsandy character of the group in this area. The limestone, though subordinate in thickness to the clay and marl, forms several definite bands that have individual physical characteristics and contain index fossils which render them readily traceable throughout the area; they have also been approximately correlated by means of the fossils with beds of corresponding age in central and southwestern Texas. The limestones are therefore valuable key beds in determining the geologic structure of the deposits.

The group has been subdivided by Hill[1] and Taff.[2] Although Hill's nomenclatural treatment is not in all respects precise and consistent, the succession of beds described by him has been substantially verified. He recognized the following divisions, named in ascending order (see Pl. XVIII): (*a*) The Preston beds, subdivided into the Kiamitia clay, thickness 40 feet, which rests upon the Goodland limestone, and the Duck Creek formation (clay, marl, and limestone), thickness 100 feet; (*b*) the Fort Worth limestone, thickness 35 feet; (*c*) the Denison beds, subdivided into (1) the Denton subgroup, thickness 45 feet; (2) the Weno subgroup, including the Marietta or Weno formation, thickness 115 feet; the Quarry limestone, thickness 2 feet; and the Pawpaw beds, thickness 45 feet; and (3) the Pottsboro subgroup, including the Main Street limestone, thickness 8 feet; and the Grayson marl, thickness 25 feet.

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[1] U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, pp. 240-292, 1901.

[2] U. S. Geol. Survey Geol. Atlas, Atoka folio (No. 79), 1902; Tishomingo folio (No. 98), 1903.

The divisions recognized by Taff in the Tishomingo and Atoka quadrangles, Okla., which correspond to the Denison beds of Hill, include in ascending order the Kiamichi formation, equivalent to the "Kiamitia" clay of Hill; the Caddo limestone, equivalent to the Duck Creek formation and the Fort Worth limestone; the Bokchito formation, equivalent to the Denton subgroup and the Weno subgroup (Marietta or Weno formation and Pawpaw beds) of Hill; and the Bennington limestone, equivalent to Hill's Pottsboro subgroup (Main Street limestone and Grayson marl). (See Pl. XVIII.)

South of Grayson and Cooke counties, Tex., the Washita group, as a whole, becomes thinner, at the same time gradually assuming a different lithologic character. In the Austin quadrangle (see Pl. XVIII) the Georgetown limestone, which is only 80 feet thick, appears to represent all of the Washita group of Grayson County up to and including the basal part of the Main Street limestone, a total thickness of at least 385 feet. However, the upper part of the Main Street limestone and the Grayson marl, which, together have a thickness of about 30 feet, become thicker toward the south and are represented in the Austin quadrangle by the Del Rio clay and Buda limestone, which have a combined thickness of about 125 feet.

Hill's classification of the group is given in Plate XVIII (p. 134), which also includes columns showing the correlation with the subdivisions of the group recognized by Taff in the Tishomingo quadrangle, Okla., by Hill in the region south of the Brazos River valley, and by Hill and Vaughan in the Austin quadrangle, Tex. In the present report Hill's classification of the group, modified somewhat for the sake of simplicity and greater clearness, is adopted, as shown in Plate XVIII, column B. The changes include the dropping of the apparently unnecessary terms Preston beds, Weno subgroup, and Pottsboro subgroup.

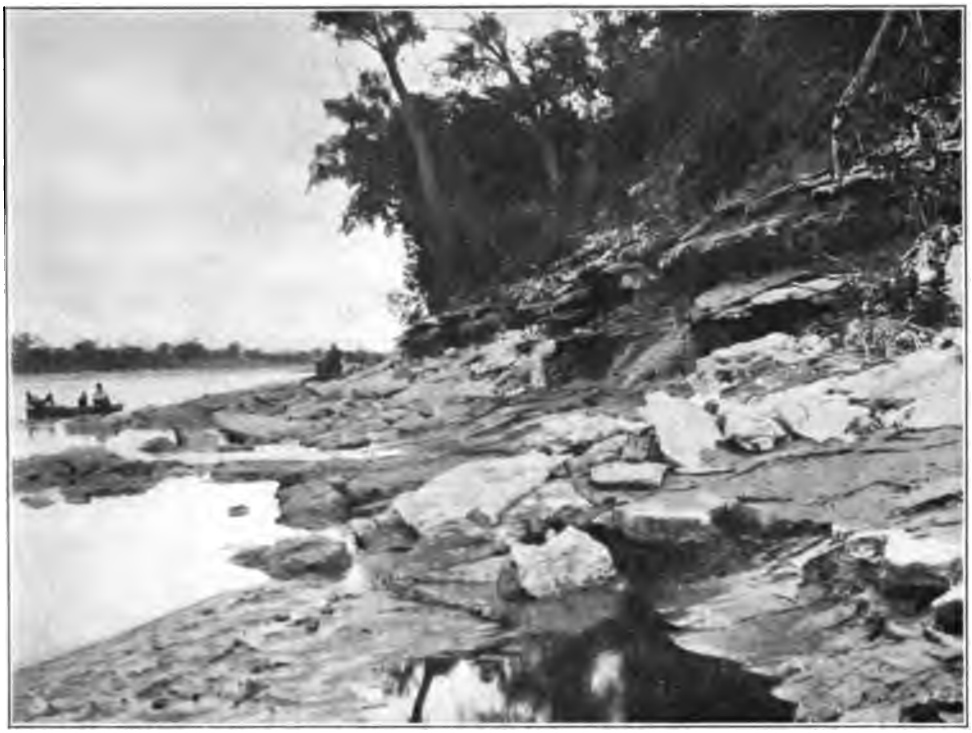
KIAMICHI CLAY.

The Kiamichi clay is named for Kiamichi River, on which it is typically exposed in Choctaw County, Okla. In Grayson County the Kiamichi clay, which includes all the beds between the Goodland and Duck Creek formations, is 40 or 50 feet thick and consists chiefly of dark carbonaceous shaly clay, with thin platy layers of siliceous limestone interbedded with the clay in the lower few feet and with thin layers of gray impure fossiliferous limestone in the upper 10 or 15 feet. The writer has not seen the full thickness of the formation, and the description is based partly on the statements of Taff and Hill. The section at Thomson Ferry, given below, which includes the upper part of the formation, was examined by the writer. (See Pl. XX.) This locality is on the north limb of the Denison anticline.

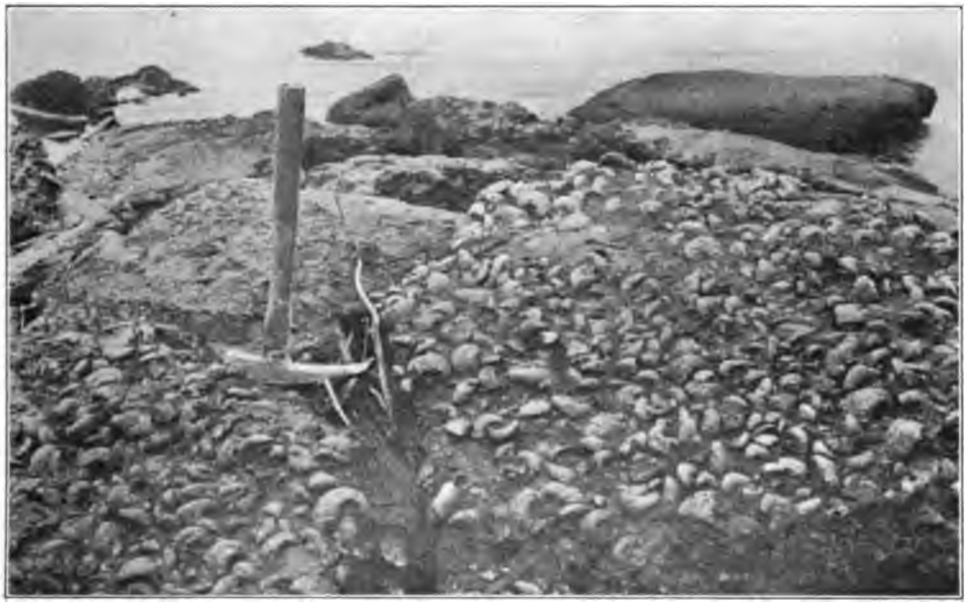
Section at Thomson Ferry, on the right bank of Red River, in Grayson County, Tex., 2 miles south of Woodville, Okla.

	Feet.
Duck Creek formation:	
Layers of limestone interbedded with subordinate layers of dark shaly calcareous clay, the limestone hard and nodular in the upper part, softer and less nodular below, especially in the lower 2 feet. Fossils recognized: *Kingena* sp., *Exogyra plexa* Cragin, *Plicatula* sp., *Gryphaea washitaensis* Hill, *Hamites fremonti* Marcou (?), *Schloenbachia* (two or three species)	15
Kiamichi clay:	
Layers of gray impure, very fossiliferous limestone with thin interbedded layers of dark calcareous shaly clay; the limestone layers contain vast numbers of *Gryphaea*, chiefly *G. navia* Hall	3½
Dark shale with layers of *Gryphaea*-bearing limestone resembling the limestone in the overlying division but more widely spaced. Fossils recognized: *Gryphaea navia* Hall, *Trigonia* sp., and *Plicatula* sp	7

The *Gryphaea*-bearing limestones in the upper part of the Kiamichi clay are characteristic and persistent and form excellent key beds in determining the structure of the rocks in this area. They were noted also on the north

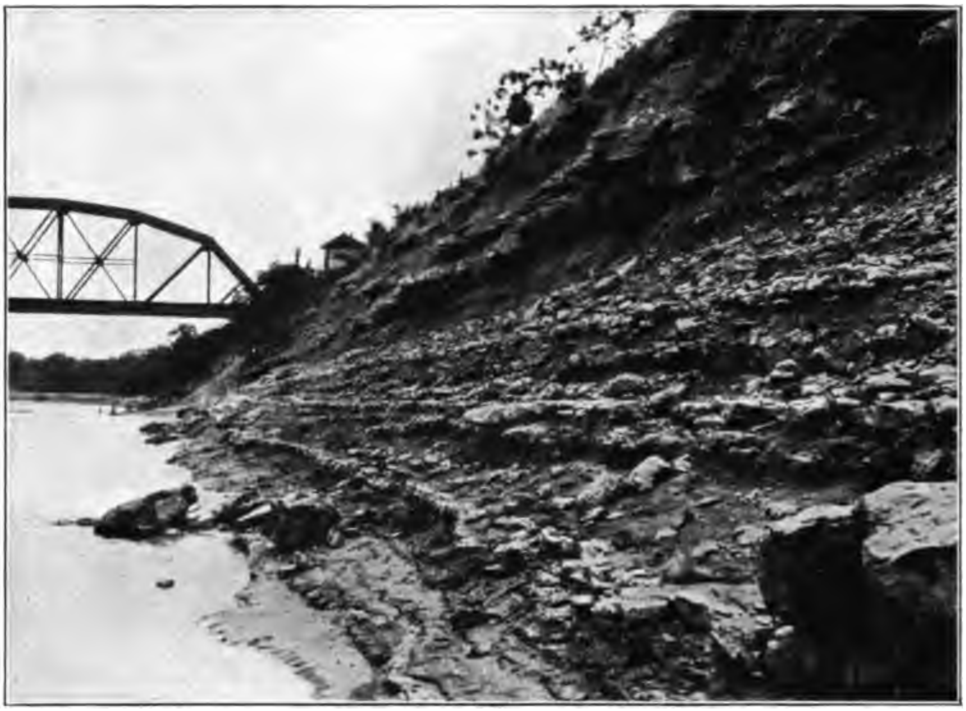


A. TOP OF KIAMICHI CLAY, OVERLAIN BY LIMESTONE MEMBER OF DUCK CREEK FORMATION, IN BLUFF ABOVE THOMSON FERRY, RED RIVER, 11 MILES NORTHWEST OF DENISON, GRAYSON COUNTY, TEX.

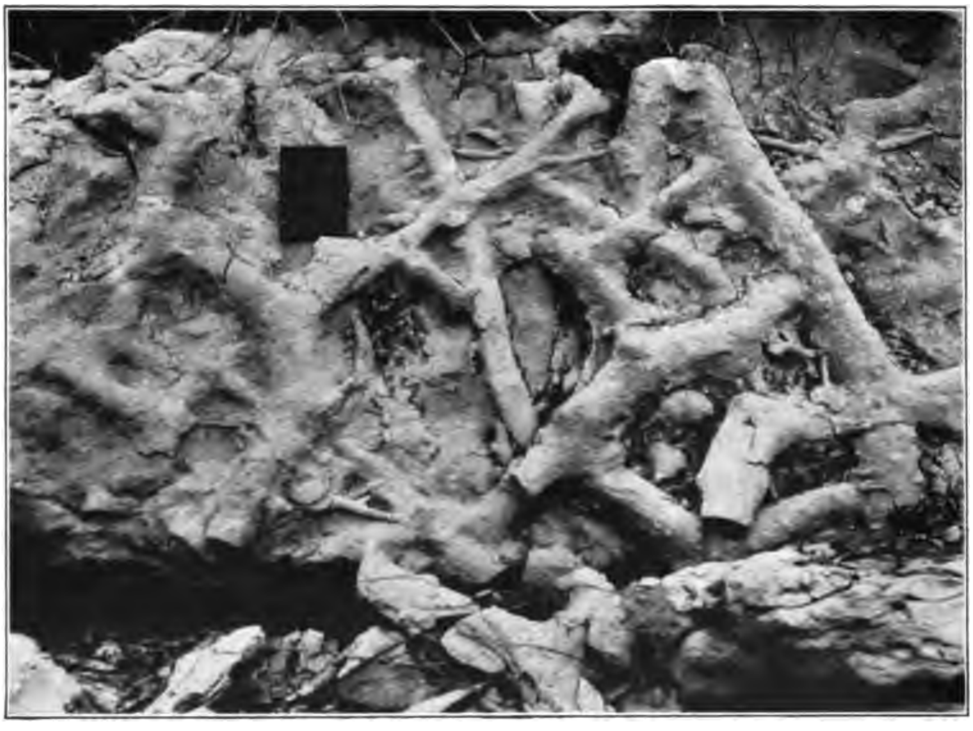


B. SLABS OF GRYPHAEA-BEARING IMPURE LIMESTONE FROM THE UPPER PART OF THE KIAMICHI CLAY AT THE LOCALITY SHOWN IN *A.*

The shells belong chiefly to the species Gryphaea navia Hall.



A. EARTHY FACIES OF THE LOWER PART OF THE FORT WORTH LIMESTONE ON THE OKLAHOMA SIDE OF RED RIVER AT THE MISSOURI, KANSAS & TEXAS RAILWAY BRIDGE 5 MILES NORTH OF DENISON, GRAYSON COUNTY, TEX.



B. FOSSIL FUCOIDS (?) ON THE UNDER SIDE OF A SLAB OF FORT WORTH LIMESTONE, AT THE LOCALITY SHOWN IN *A*.

limb of the Preston anticline in a branch of Rock Creek at a public road crossing 3 miles south by west of Kingston, Marshall County, Okla. On the south limb of the anticline they were examined along the Preston road a short distance south of Rock Bluff (see p. 134); along the road leading down to Henderson Ferry, 5½ miles north by west of Pottsboro; and in the bed of Little Mineral Creek, 3½ miles north of Pottsboro.

DUCK CREEK FORMATION.

The Duck Creek formation, which is typically exposed on Duck Creek north of Denison, in Grayson County, consists of approximately 100 feet of limestone and gray to greenish-gray shaly calcareous clay, which intervene between the Kiamichi clay below and the Fort Worth limestone above. In the lower 35 or 40 feet the limestone alternates with the clay in layers 6 to 12 inches thick, in about equal proportions; in the upper part of the section the clay predominates, the limestone layers being rather soft and separated by intervals of 2 to 3 feet or more of clay. The limestones in the lower 35 or 40 feet are characterized by keeled and nonkeeled ammonites, many of which reach a diameter of 2 feet or more. One layer of white, chalky limestone 3 or 4 feet thick 35 or 40 feet above the base of the formation and 2 or 3 feet of gray calcareous clay that immediately underlies it contain great numbers of large ammonites and form a zone that has been recognized in outcrops over a large area in Texas and Oklahoma and was used by Messrs. Hopkins, Powers, and Robinson as a key in the determination of structure. The keeled ammonites belong chiefly to the genus *Schloenbachia*, several species of which have been differentiated. The nonkeeled forms belong chiefly to the species *Pachydiscus brazoensis* (Shumard). The limestones also contain some of the remains of the problematic organisms (fucoids?), such as occur in great numbers and of larger size in the Fort Worth limestone. (See p. 140 and Pl. XXI, *B*.) The most complete section of the Duck Creek formation examined by the writer is on Duck Creek and in a cut of the St. Louis & San Francisco Railroad where it comes close to Duck Creek, 2¾ miles north of Denison.

Section on Duck Creek and in a cut of the St. Louis & San Francisco Railroad 2¾ miles north of Denison, Grayson County, Tex.

	Feet.
Fort Worth limestone:	
Four or five layers of nodular impure argillaceous fossiliferous limestone interbedded with gray shaly clay	8
Duck Creek formation:	
Gray shaly calcareous clay with interbedded layers of impure non ledge-forming limestone at intervals of 2 or 3 feet	22
Concealed	20
Greenish-gray calcareous clay from which weather numerous specimens of *Plicatula* cf. *P. incongrua* Conrad and small rusty ammonites, probably the young of *Pachydiscus* and *Schloenbachia*, also a few specimens of *Gryphaea washitaensis* Hill	15
Ledges of limestone with interbedded layers of gray shaly clay, poorly exposed; the limestone, especially one layer near the top, contains numerous keeled and nonkeeled ammonites, many of which are of large size (maximum, 2 feet in diameter)	20
Alternating beds of ammonite-bearing limestone and gray shaly clay, about half and half, well exposed in bluff along the creek	20

Other exposures of the limestones forming the lower part of the Duck Creek formation were observed by the writer in a small branch of Little Mineral Creek at the crossing of the road leading to Henderson Ferry, 4¾ miles north of Pottsboro; in the road leading down to Henderson Ferry about a mile west by north of the locality just mentioned; and at Willis Ferry (Oklahoma side), 13 miles northwest of Pottsboro, Tex. The upper part of the Duck Creek, consisting of calcareous clay, which lacks conspicuous layers of limestone, is well exposed in a bluff on the north side of Red River, about half a mile above Willis Ferry. These localities are on the south limb of the Preston anticline; the section at Thomson Ferry, on the north limb of the anticline described on page 138, reveals the basal 15 feet of the limestone.

FORT WORTH LIMESTONE.

The Fort Worth limestone, named from the city of Fort Worth, Tarrant County, Tex., consists in the vicinity of Red River north of Denison, Grayson County, of about 25 feet of gray nodular earthy limestone interbedded with layers of dark shaly clay, followed above by 8 to 10 feet of heavy-bedded hard cream-colored chalky limestone. This limestone resembles the limestone portion of the underlying Duck Creek formation, from which it may be distinguished by slight lithologic differences, by the more common occurrence of pectens, by the presence of echinoids in greater number and of larger size, and by the greater abundance and larger size of the problematic fucoid-like remains described below. The Fort Worth is immediately overlain by the Denison formation. A good exposure of the lower 25 feet of the formation is afforded by the bluff of Red River at the north end of the bridge of the Missouri, Kansas & Texas Railway 5 miles north of Denison, on the north limb of the Preston anticline. (See Pl. XXI, *A*.) Here the impure nodular limestone layers range in thickness from a few inches to 2 feet, and the interbedded shaly clay composes half or more of the bulk of the material. The limestone layers are fossiliferous and the most numerous and conspicuous forms are keeled ammonites, some of which have a maximum diameter of 18 inches, and echinoids. An interesting and characteristic feature of these limestones is the problematic fucoid (?) remains or casts of borings (?) which line the underside of some of the limestone layers. Good examples are shown in Plate XXI, *B*. The upper part of the formation is well exposed in the bank of a small branch about a third of a mile northeast of the Missouri, Kansas & Texas Railway bridge just east of the railway track; here the Fort Worth is overlain by 15 feet of reddish terrace sand.

The upper heavy-bedded cream-colored limestone of the Fort Worth is exposed at many places on the south limb of the Preston anticline in Grayson County and was observed in a cut of the Missouri, Kansas & Texas Railway 2 miles north by east of Denison; on the Bears Ferry road 1¾ miles in an air line northwest of the post office at Denison; on the Preston (Rock Bluff) road 3¼ miles north of the Missouri, Kansas & Texas Railway, near the head of a branch of Little Mineral Creek; on the public road 2½ miles in an air line northeast of Pottsboro; and on the Henderson Ferry road 3¼ miles north of Pottsboro, an eighth of a mile north of Fink. This upper massive part of the Fort Worth limestone constitutes a good key bed, owing to its ledge-forming character and its characteristic fossils, among which are *Hemiaster elegans* Shumard, *Exogyra walkeri* White (a large smooth species), *Nautilus texanus* Shumard, and *Schloenbachia leonensis* Conrad.

DENISON FORMATION.

DENTON CLAY MEMBER (INCLUDING "OSTREA CARINATA BED").

Hill[1] originally applied the name Marietta to beds, chiefly shaly clays, 160 feet thick, between the Fort Worth limestone below and imperfectly defined so-called North Denison sands above. Later he reclassified the Denison formation, as shown in Plate XVIII, column C, introducing the name Denton subgroup, from Denton Creek, Denton County, for the lower 45 feet of the original Marietta, including the "*Ostrea carinata* bed" at its top, and applying the name Weno formation to the beds which lie between the Denton and the "Quarry" limestone and include most of the upper part of the original Marietta. In one of his tables in the same paper[2] he somewhat loosely applied the name Marietta to the beds between the Denton and Pawpaw divisions. As the name Marietta is preoccupied for sandstone in the Dunkard group of Pennsylvania, West Virginia, and Ohio, its use in the Denison section seems undesirable.

The lower 5 feet of the Denton is a strongly calcareous clay of a decided marly character. This is followed by 35 feet of shaly, less calcareous clay, which in turn is followed by 3 to 5 feet of highly fossiliferous impure limestone, composed largely of the shells of *Gryphaea washitaensis* Hill but containing also a few large echinoid spines and other fossils, among which are considerable numbers of *Ostrea carinata* Lamarck, a fossil which suggested the name "*Ostrea carinata* bed." The Denton member appears in imperfect exposures along the St. Louis & San Francisco Railroad 1½ to 2 miles north of Denison.

The "*Ostrea carinata* bed" appears in many small exposures along the south limb of the Preston anticline and is an excellent key rock, chiefly because of the presence of *O. carinata* Lamarck, a peculiar and easily recognizable fossil. This stratum is exposed on the St.

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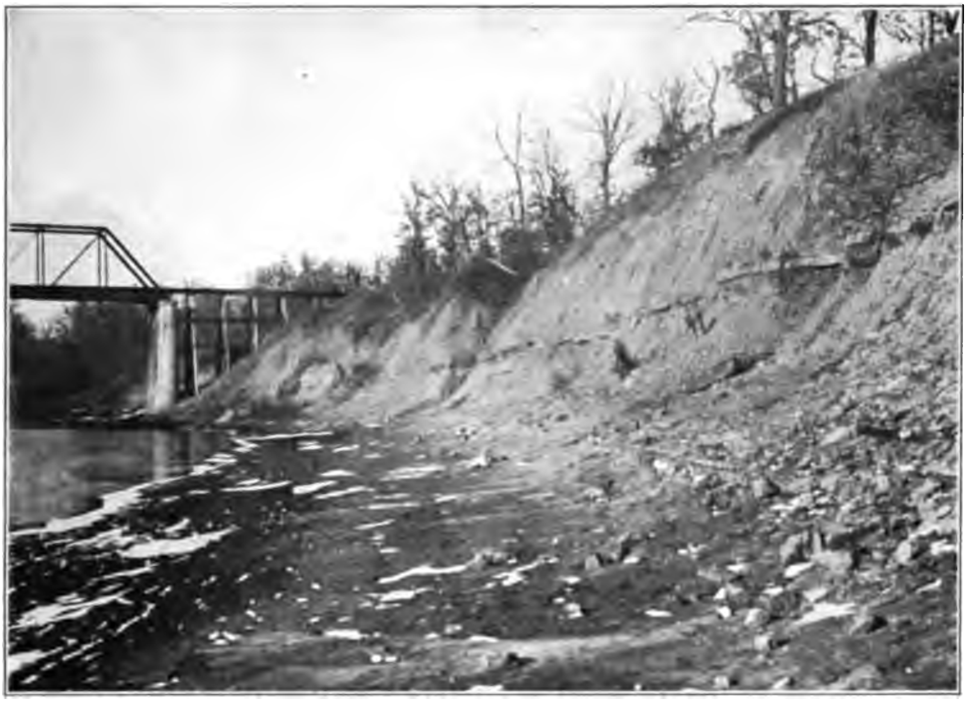
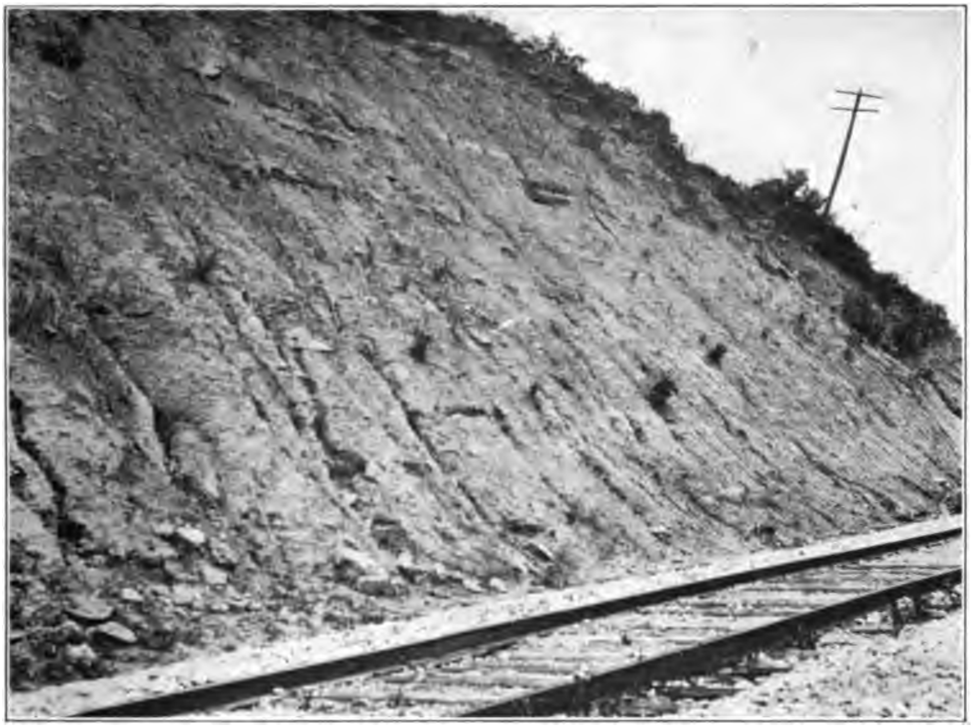
[1] Hill, R. T., Geol. Soc. America Bull., vol. 5, p. 303, 1894.

[2] Hill, R. T., U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, p. 115, 1901.



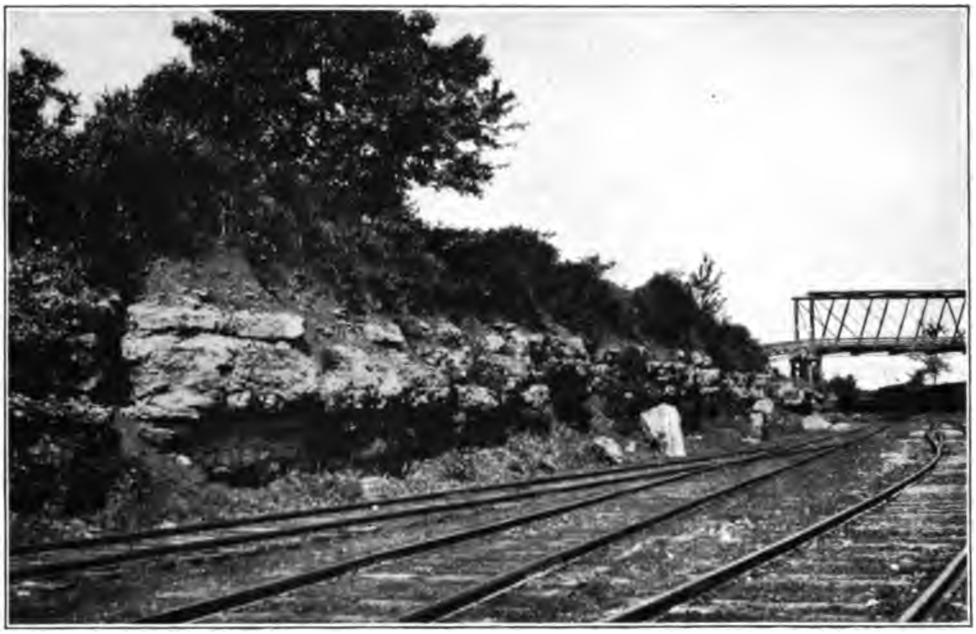
A. UPPER PART OF THE WENO CLAY IN THE EAST BANK OF WASHITA RIVER AT THE FRISCO RAILROAD BRIDGE 2¼ MILES WEST OF PLATTER, BRYAN COUNTY, OKLA.

The material exposed in the bank comprises shaly clay and subordinate interbedded layers of sandstone.

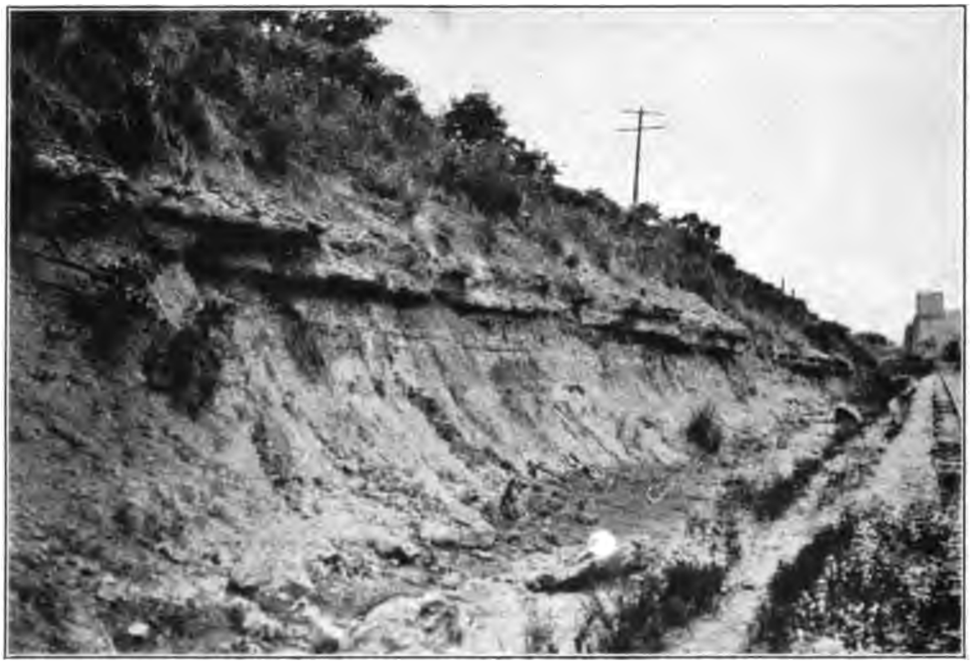


B. UPPER PART OF THE WENO CLAY IN A CUT OF THE FRISCO RAILROAD A MILE NORTH OF THE STATION AT DENISON, GRAYSON COUNTY, TEX.

A ledge of the "Quarry" limestone, which overlies the Weno, appears at the extreme top of the section.



A. MAIN STREET LIMESTONE IN A CUT OF THE MISSOURI, KANSAS & TEXAS RAILWAY 3 MILES WEST OF THE STATION AT DENISON, GRAYSON COUNTY, TEX.



B. "QUARRY" LIMESTONE, UNDERLAIN BY THE WENO CLAY, IN A CUT OF THE FRISCO RAILROAD THREE-QUARTERS OF A MILE NORTH OF DENISON, GRAYSON COUNTY, TEX.

Louis & San Francisco Railroad 1½ miles north of Denison and was seen also on the Missouri, Kansas & Texas Railway 1¼ miles north of Denison; on the Bears Ferry road about 1½ miles in an air line northwest of the post office at Denison; in the headwater branches of Shawnee Creek, 3½ miles west by north of the post office at Denison; and at Fink post office, 3 miles north of Pottsboro. Messrs. Hopkins and Powers noted outcrops of a stratum that carries *O. carinata* Lamarck and apparently represents the "*Ostrea carinata* bed" stratigraphically 55 feet above the Fort Worth limestone, at two localities on the north limb of the anticline in Marshall County, Okla., namely, 3¼ miles southeast of Kingston, in the NE. ¼ sec. 3, T. 7 S., R. 6 E.; and 2½ miles east of Kingston, in the SE. ¼ sec. 28, T. 6 S., R. 6 E.

WENO CLAY MEMBER.

The Denton clay member is overlain by 115 feet of dark-gray shaly clay with subordinate thin partings, lenses, and layers of fine gray to yellow sand, some of which are indurated to ledge-forming sandstone. To this material Hill[1] gave the name Weno formation, from the small village of Weno, on Red River 5 miles northeast of Denison, Grayson County, which does not appear on recent maps and is apparently abandoned. Hill in the same paper also used the name Weno in a broader ("subgroup") sense, to include both the Weno clay member and the overlying Pawpaw sandy member, a usage not followed in the present paper. Sand layers are numerous, though subordinate to the clay, in the upper 35 feet of the division in cuts of the St. Louis & San Francisco Railroad about a mile north of the station at Denison (see Pl. XXII, *B*), where one lens has a maximum thickness of 1½ feet. At the same locality the clays contain many small flattish ferruginous concretions, probably derived by oxidation from concretions of iron carbonate, and some small concretions of marcasite. Fossil pelecypods and gastropods in a good state of preservation are numerous in the clays, sands, and ferruginous concretions in these upper beds, among which were recognized *Nucula* sp., *Ostrea quadriplicata* Shumard, *Protocardia texana* (Conrad), *Cyprimeria* sp., *Corbula* (three species), *Cymbophora* sp., *Turritella* sp., *Auchura mudgeana* White, *Engonoceras serpentinum* (Cragin).

The Weno clay weathers down to smooth surfaces and is as a rule poorly exposed on the uplands and valley slopes. In addition to the section in the railroad cut just described, a good exposure of strata believed to represent a portion of the Weno clay and certainly representing either this clay or the Pawpaw member is afforded by Carpenters Bluff, on Red River below the bridge of the Missouri, Oklahoma & Gulf Railway, 7 miles in an air line due east of Denison. Hill mapped the area in which this bluff is included as belonging to the Woodbine formation, though Taff had at an earlier date recognized that the outcrop at the bluff belonged to the Washita group. This exposure is about on the southeastward-plunging axis of the Preston anticline.

According to Messrs. Hopkins and Powers the Weno clay in the north limb of the Preston anticline in Marshall County, Okla., is about 135 feet thick, or 20 feet thicker than in the south limb in Grayson County, Tex. A fine exposure of the upper 50 feet of the Weno, overlain by the "Quarry" limestone, is afforded by a bluff on the left bank of Washita River at the crossing of the St. Louis & San Francisco Railroad 2¾ miles west of Platter, Bryan County, Okla. A view of this bluff, taken at a low stage of water, is shown in Pl. XXII, *A*. The beds here consist predominantly of greenish shaly calcareous clay, with an interstratified layer of sandstone 5 or 6 feet below the "Quarry" limestone and several layers of thin flaggy sandstone 25 to 40 feet below the "Quarry." Well-preserved fossil shells, many species of which are identical with those collected in a cut of the St. Louis & San Francisco Railroad a mile north of Denison in Grayson County, Tex., are abundant in some layers of the clay and in some of the indurated layers. Several well-preserved fragments of crustaceans were found in the talus.

About 20 feet of dark shaly clay of the Weno member, containing poorly preserved fossils, is well exposed in the left bank of a branch just east of the Missouri, Kansas & Texas Railway, 1½ miles south of Colbert, Bryan County, Okla.; this locality also is on the north limb of the Preston anticline.

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[1] Hill, R. T., U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, pp. 121, 274, 1901.

PAWPAW SANDY MEMBER (INCLUDING "QUARRY" LIMESTONE).

The Weno clay member is overlain by approximately 50 feet of more or less irregularly bedded clays and sands, including at the base a persistent layer of sandy limestone 1 to 4 feet thick, known as the "Quarry" limestone. Calcareous clay predominates in the lower half of the division above the "Quarry" limestone, and sand and interbedded laminated sand and clay predominate in the upper half. Good exposures, particularly of the upper part of the member, occur in the headwater branches of Pawpaw Creek within the corporate limits of the eastern part of Denison.

The "Quarry" limestone is a sandy bluish-gray limestone that weathers yellow and purple and contains considerable numbers of *Ostrea quadriplicata* Shumard. *Ostrea subovata* Shumard is rather sparingly represented. A good exposure is afforded by a cut of the St. Louis & San Francisco Railway three-quarters of a mile north of the station at Denison (see Pl. XXII, *B*), where it is 2 feet thick and the lower 3 to 12 inches is conglomeratic. The somewhat scattered pebbles in the conglomeratic portion consist of waterworn calcareous sandstone, sandy limestone, and calcareous and ferruginous concretions, the largest 3 inches or more in length. A few borings into the top of the underlying Weno clay, filled with material characteristic of the limestone, were noted. As the base of the limestone is sharply separated from the underlying clay and is somewhat undulating, the contact appears to mark an unconformity, though the time represented by it was probably short. The limestone in this section is overlain by 4 feet of clay, above which is another layer of similar limestone 6 inches to 1 foot thick, which shows the lenticular character of the rock and which apparently connects the "Quarry" limestone more closely with the overlying Pawpaw member than with the underlying Weno clay. In this connection it may be mentioned that Messrs. Hopkins and Powers have noted in Marshall County, Okla., several layers of sandy limestone in the Pawpaw member that resemble the "Quarry."

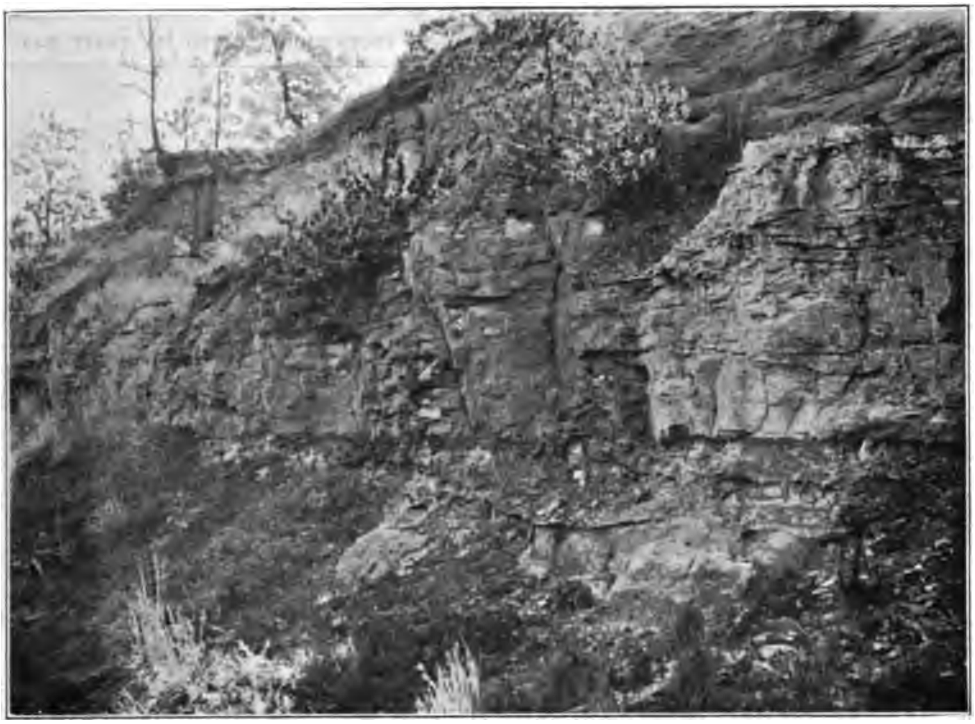
Other outcrops of the limestone were examined in Grayson County in the bed of a small branch of Smith Creek just south of the Missouri, Oklahoma & Gulf Railway, 4¾ to 5½ miles east of Denison; in a ditch and in a field south of the Missouri, Oklahoma & Gulf Railway about 2½ miles east of Denison; at a culvert of the Missouri, Oklahoma & Gulf Railway about 2 miles east of Denison; in a north-south public road 1½ miles east by north of Pottsboro; in an east-west road at two creek crossings 2 miles north of Pottsboro; in the Henderson Ferry road 2¾ miles north of Pottsboro, a quarter of a mile south of Fink; and in the public road a quarter of a mile west of Fink.

On the north limb of the Preston anticline the "Quarry" limestone outcrops at the crest of the steep part of the bluff on Washita River at the crossing of the St. Louis & San Francisco Railway in Bryan County, Okla. (see p. 141), where it overlies the Weno clay and is overlain in turn by clays and sands of the Pawpaw member. Poor exposures were also noted near the public road leading to Kingston, about 3 miles northwest of Woodville, in Marshall County, Okla. Messrs. Hopkins and Powers state that in the latitude of Kingston and farther north there is no definitely recognizable "Quarry" limestone, but several beds resembling it; 3 miles east of Kingston they examined a section which included four distinct layers of sandy limestone each resembling the "Quarry" and each containing *Ostrea quadriplicata* Shumard. Mr. Hopkins noted an outcrop of a sandy glauconitic limestone resembling the "Quarry" 4 miles east of Kingston, Marshall County, in the center of the west line of sec. 35, T. 6 S., R. 6 E., from which he obtained a specimen of a bryozoan which R. S. Bassler refers to the genus *Domopora*.

The section described below shows the relation of the Pawpaw member to the overlying Main Street limestone member. (See Pl. XXIV, *B*.)

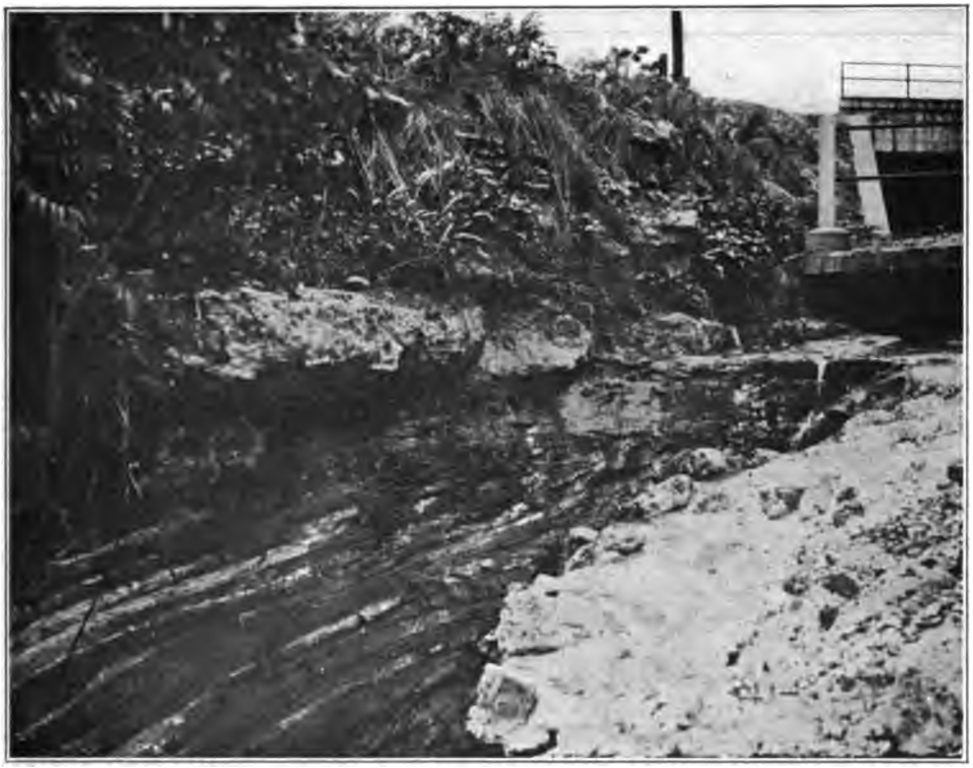
Section in a small headwater branch of Pawpaw Creek just east of the subway under the Missouri, Kansas & Texas Railway south of the station at Denison, Tex.

	Feet.
Main Street limestone member:	
Irregular nodular layers of hard limestone 6 to 18 inches thick, interbedded with soft yellow marl a few inches to 6 inches thick; the under side of the lowest limestone layer is roughly nodular. *Exogyra arietina* Roemer occurs abundantly in the upper 2 or 3 feet	8
Gray, faintly laminated sandy and calcareous (marly) clay, coarsely sandy in the basal few inches; in the basal 6 inches are numerous small ferruginous concretions and a few flattish, partly oxidized iron carbonate concretions; one apparently water-worn quartzitic sandstone pebble was noted	1½–2



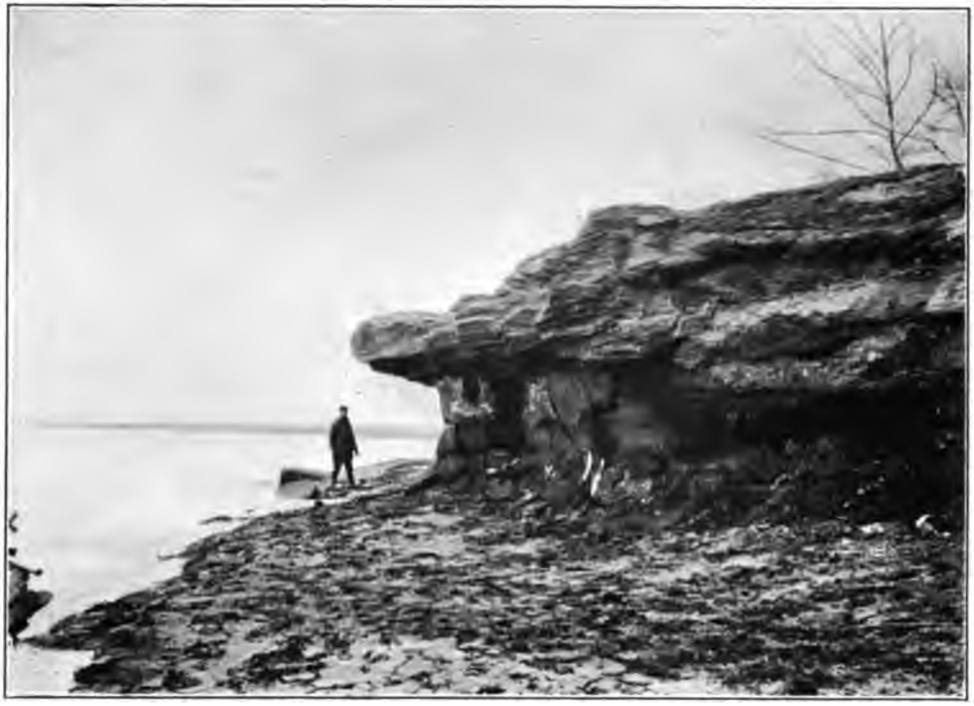
A. WOODBINE SAND IN A CUT OF THE MISSOURI, KANSAS & TEXAS RAILWAY 1½ MILES WEST BY SOUTH OF THE STATION AT DENISON, GRAYSON COUNTY, TEX.

The Woodbine here is a partly indurated ferruginous sand, containing irregularly distributed thin ironstone plates.

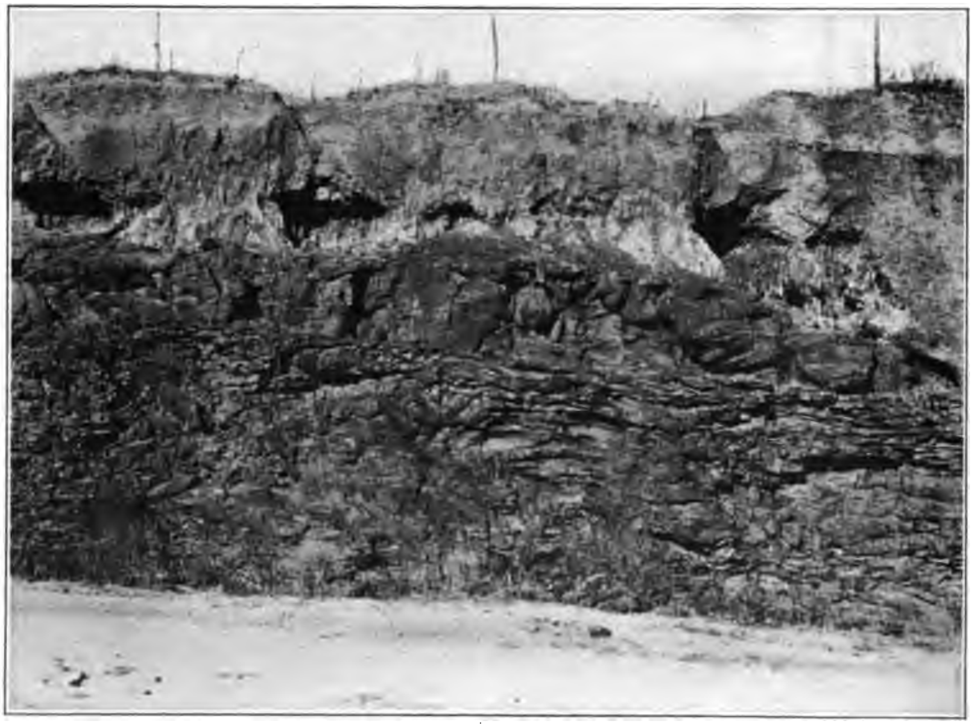


B. MAIN STREET LIMESTONE UNDERLAIN BY THE PAWPAW SANDY MEMBER OF THE DENISON FORMATION NEAR THE SUBWAY SOUTH OF THE MISSOURI, KANSAS & TEXAS RAILWAY STATION AT DENISON, GRAYSON COUNTY, TEX.

The Pawpaw member, as exposed at this locality in a headwater branch of Pawpaw Creek, comprises laminated cross-bedded sand and clay.



A. SAND AND CLAY OF THE WOODBINE FORMATION AT HYATTS BLUFF, ON RED RIVER 5 MILES NORTHWEST OF RAVENNA, FANNIN COUNTY, TEX.



B. FERRUGINOUS SAND OF THE WOODBINE FORMATION IN THE SHERMAN ROAD, 2 MILES SOUTHWEST OF DENISON, GRAYSON COUNTY, TEX.

	Feet.
Unconformity (?).	
Pawpaw sandy member:	
Thinly laminated, strongly cross-bedded gray clay and sandy clay with thin sand partings and some larger lenses of fine yellow sand; numerous thin iron crusts occur in the partings; some comminuted plant fragments were noted	6

The upper 6 feet of the Pawpaw is also well exposed beneath the Main Street limestone on the Missouri, Kansas & Texas Railway at the iron overhead bridge 3 miles west of the station at Denison. (See below and Pl. XXIII, *A*.) Here the Pawpaw consists of current-bedded, laminated sand and clay with highly fossiliferous thin lenses of ferruginous oxidized soft sandstone. Among the fossils recognized were *Nucula* sp., *Protocardia texana* (Conrad), *Cymbophora* sp., *Corbula* sp., *Anchura mudgeana* White, and *Engonoceras serpentinum* (Cragin).

The Pawpaw member produces a narrow belt of sandy soil between the clay soils of the Weno and those of the overlying Main Street limestone and the Grayson marl. The topography produced by the sandy beds of the Pawpaw is similar to that characteristic of the outcrop of the Woodbine formation of the Gulf series.

MAIN STREET LIMESTONE MEMBER.

The Main Street limestone, named from exposures on Main Street in Denison, consists, in Grayson County, of 8 to 20 feet or more of heavy-bedded hard limestone, with subordinate interbedded layers of unconsolidated calcareous marl, and is characterized by the presence of *Exogyra arietina* Roemer, particularly in the upper part, and of *Kingena wacoensis* (Roemer) in the lower part. One of the best exposures of the limestone is afforded by a cut of the Missouri, Kansas & Texas Railway 3 miles west of the station at Denison. (See Pl. XXIII, *A*.)

Section in cut of Missouri, Kansas & Texas Railway 3 miles west of the station at Denison, Grayson County, Tex.

	Feet.
Residuum and creep:	
Brownish loam containing in places along its base a great number of ferruginous sandstone fragments and boulders derived from the Woodbine sand	2–6
Main Street limestone member:	
Irregular layers of limestone 3 to 4 feet thick, with discontinuous interbedded lenses of soft marl, underlain by 3 to 4½ feet of massive hard limestone having an undulating nodular base; *Exogyra arietina* Roemer is common in the upper layers	7½
Main Street limestone member—Continued.	
Greenish-gray sandy calcareous clay marl with scattered white clay pebbles and ferruginous concretionary clay nodules along the base, some of which suggest having been mechanically included	1¼–1½
Unconformity (?).	
Pawpaw sandy member:	
Current-bedded greenish-gray fine sand, with fine clay laminae and subordinate lenses of laminated clay. Highly fossiliferous thin discontinuous lenses of ferruginous oxidized soft sandstone with many molds and internal casts of fossil mollusks; soft molds and internal casts occur also in the soft sands. (See list, above.) Maximum exposed thickness	6

The limestone is poorly exposed on Main Street east of the railroad tracks in the eastern part of Denison and is well exposed in some of the branches and on the slopes about the headwaters of Pawpaw Creek in the same vicinity. One section is described on page 122. (See also Pl. XXIV, *B*.)

Other exposures of the limestone were noted along the south limb of the Preston anticline in Grayson County, in the bed of a headwater branch of Iron Ore Creek just north of the Missouri, Kansas & Texas Railway, 5¼ miles west of the station at Denison and a quarter of a mile east of a north-south public road; poor exposures showing dips of 20° or more in a low strike ridge extending from a point 2 miles east of Pottsboro northwestward for a distance of 2 miles; in the bed of a headwater branch of Little Mineral Creek on the Henderson Ferry road 2½ miles north of Pottsboro, seven-eighths of a mile south of Fink; poor exposures along the east-west public road three-fourths of a mile to 1½ miles west of Fink; on the same road near the heads of ravines 2¼, 2½, 2¾, and 3⅛ miles west of Fink, overlain by the Grayson marl, which appears in several poor exposures; in the bed of a small southward-flowing branch of Mill Creek about 4 miles west by north of Fink; along a north-south public road 2 miles east by south of Cedar Mills; on a public road on the westward-facing slope of the Mineral Creek valley 1½ miles east by south of Cedar Mills; in a small branch at the turn of the road just south of Cedar Mills; on the northward-facing slope of the Sandy Creek valley just north of Cedar Mills; at the crossing of a public road over a headwater branch of Brier Creek 5 miles northwest of Gordonville; and on the southeast crest of Brushy Mound, 9 miles northwest of Gordonville.

The Main Street limestone was not seen in place by the present writer on the north limb of the Preston anticline, but Messrs. Hopkins and Powers state that they have seen it well exposed at the following localities in Oklahoma: In Bryan County on the south bank of Rock Creek along the public road, 2 miles northwest of Platter; and in Marshall County a mile west of Washita River; on the south bluff of Washita River at the southeast corner of sec. 7, T. 7 S., R. 7 E.; 2 miles northeast of Woodville, in the center of the east line of sec. 19, T. 7 S., R. 7 E.; and 4 miles north of Woodville, in the NW. ¼ sec. 1, T. 7 S., R. 6 E. According to the geologic map of the Tishomingo quadrangle, which joins the Denison quadrangle on the north, the Bennington limestone of Taff, which includes the Main Street limestone, enters the Denison quadrangle 2 or 3 miles west of its northeast corner.

GRAYSON MARL MEMBER.

The topmost division of the Denison formation and of the Washita group, known as the Grayson marl, consists of 15 to 25 feet of light greenish-gray calcareous clay or marl with lumps of white lime and several nodular thin layers of limestone. The fossils carried by the marl include species of *Gryphaea*, *Pecten*, *Trigonia*, *Plicatula*, *Protocardia*, *Turrilites*, and *Hoplites*, of which *Gryphaea mucronata* Gabb is perhaps the most common.

The marl is poorly exposed above the Main Street limestone about the headwater branches of Pawpaw Creek, in the eastern part of Denison. The best exposure examined was in a pit south of the Missouri, Oklahoma & Gulf Railway about a quarter of a mile east of the station at Denison, where a thickness of 16 feet of the marl was noted.

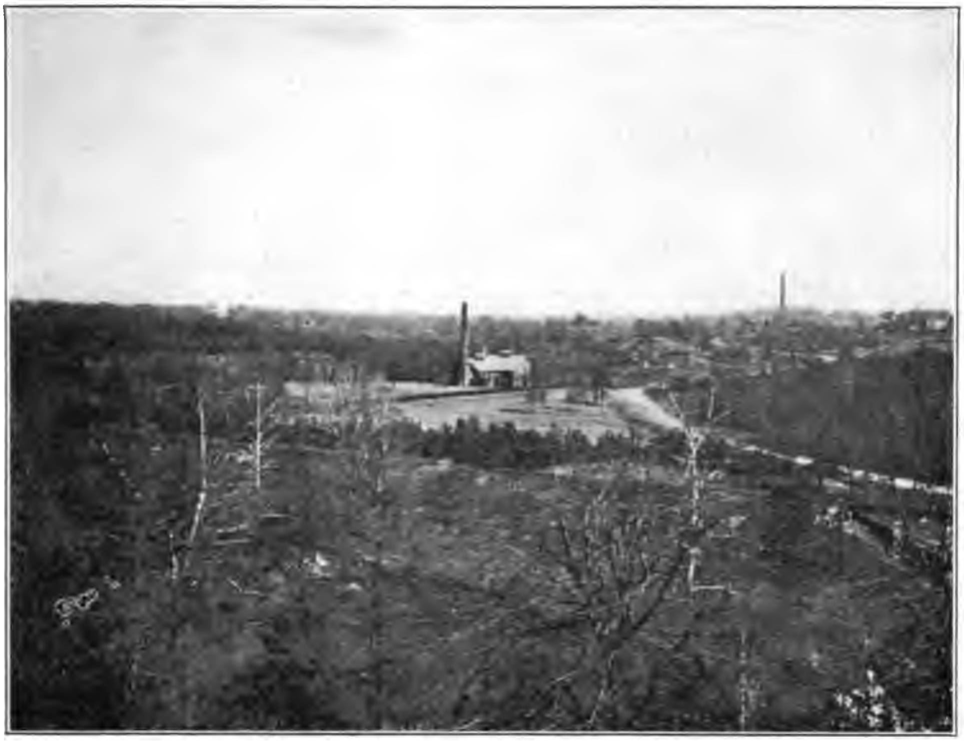
Other exposures in Grayson County occur in the banks of headwater branches of Iron Ore Creek near the Missouri, Kansas & Texas Railway 5¼ to 5½ miles west of Denison; in the bank of a headwater branch of Little Mineral Creek near the crossing of the Henderson Ferry road, 2½ miles north of Pottsboro and seven-eighths of a mile south of Fink; and at intervals on and near the public road leading west from Fink for a distance of about 4 miles.

GULF SERIES.

GENERAL CHARACTER.

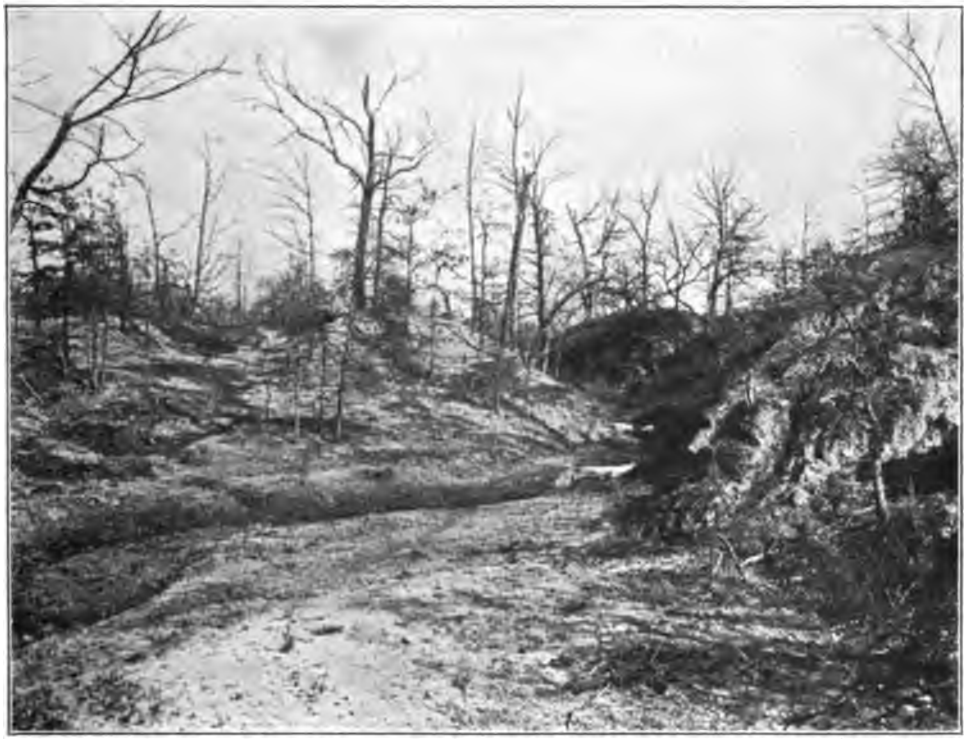
The Gulf series is composed of sands, shaly clays, chalks, and calcareous clays and sands (marls), which have an estimated thickness of approximately 3,000 feet in the area under consideration. In the southwestern part of the area the succession of formations in the series is, in ascending order, as follows: Woodbine sand, Eagle Ford clay, Austin chalk, Taylor marl (including the Wolfe City and Pecan Gap members; see pp. 155–156), and Navarro formation. Toward the north the lower part of the Austin chalk merges, with some intertonguing, into contemporaneous nonchalky sands and clays, and the upper part of the Austin transgresses to a higher position in the geologic column, so that in Fannin and Hunt counties the following succession of mappable units is recognizable: Woodbine sand, Eagle Ford clay, unnamed clays and sands beneath the Austin chalk, Ector tongue of Austin chalk, unnamed clay in the vicinity of Bonham, Annona tongue of Austin chalk, Taylor marl (including Wolfe City and Pecan Gap members), and Navarro formation. Still farther to the northeast, in Lamar, Delta, and Hopkins counties, the succession of units is as follows: Woodbine sand (exposed at Arthurs Bluff, on Red River), Eagle Ford formation (largely concealed by terrace deposits), unnamed sands and clays (also largely concealed), Blossom sand, Brownstown marl, Annona tongue of Austin chalk, Taylor marl, and Navarro formation. The age relations of the units just named in different parts of the area are diagrammatically represented in the correlation section given in Plate XXX, *C* (p. 155).

The Gulf series is referable in its entirety to the Upper Cretaceous, though, as indicated on page 134, it may not include representatives of the lowermost part of the Upper Cretaceous. The nature of the contact separating the Gulf series from the underlying Comanche series has not been satisfactorily determined in northeastern Texas. Probably it is that of unconformity, the basal formation of the upper series, the Woodbine sand, having been deposited in the shallow waters of the transgressing sea, in the deeper waters of which the succeeding truly marine sediments of the series were

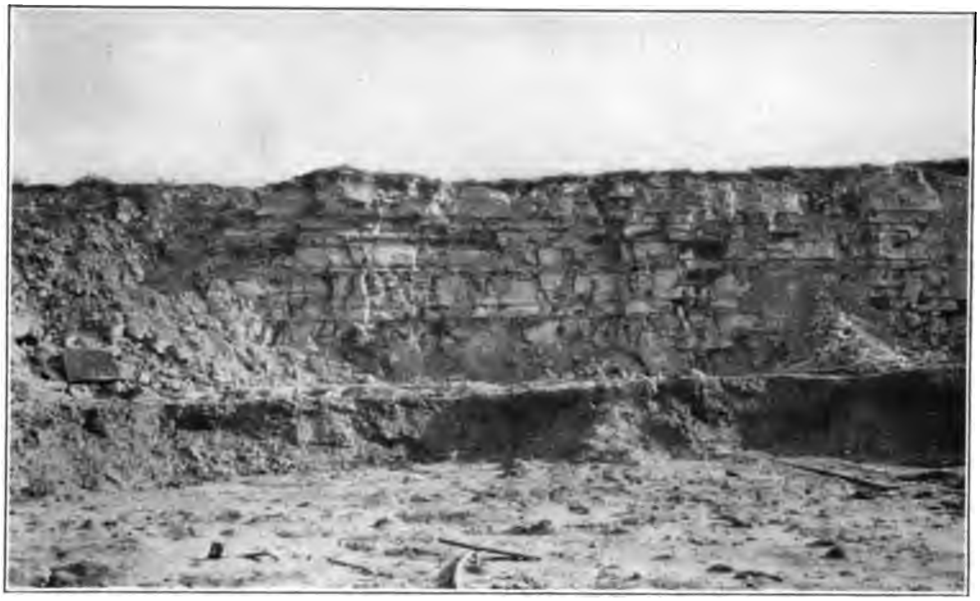


A. TOPOGRAPHY IN THE HILLY AREA UNDERLAIN BY THE WOODBINE SAND 1¾ MILES SOUTHWEST OF DENISON, GRAYSON COUNTY, TEX.

View looking northeast toward the old waterworks plant.

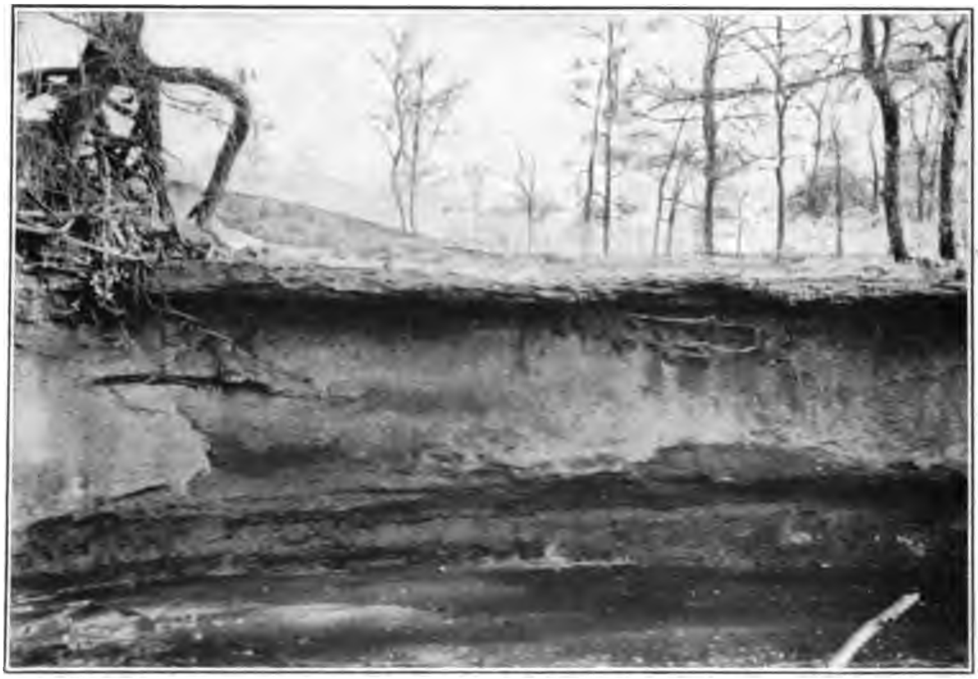


B. A DETAIL OF TOPOGRAPHY IN A SMALL BRANCH VALLEY UNDERLAIN BY THE WOODBINE SAND 1½ MILES SOUTHWEST OF DENISON, GRAYSON COUNTY, TEX.



A. CONTACT BETWEEN THE EAGLE FORD CLAY AND THE AUSTIN CHALK IN A QUARRY OF THE TEXAS PORTLAND CEMENT CO. 3 MILES WEST OF DALLAS, TEX.

The contact between the Eagle Ford clay and the Austin chalk is approximately marked by the crest of the prominent bench in the foreground.



B. "FISH-BED CONGLOMERATE" (?) IN THE BED OF A BRANCH 3 MILES SOUTH OF RAVENNA, FANNIN COUNTY, TEX.

The indurated conglomeratic layer is immediately underlain by somewhat argillaceous fine marine sand, which here forms the topmost stratum of the Eagle Ford clay.

laid down. Toward the south the Woodbine sand becomes progressively thinner, finally disappearing in McLennan County, south of which the Eagle Ford clay rests directly upon the Buda limestone of the Comanche series. The absence of the Woodbine in central and southwestern Texas would therefore seem to indicate unconformity, unless the age equivalent of the Woodbine lies in the relatively thin sediments that compose the Buda limestone, a supposition which seems highly improbable and which has no basis of known fact.

WOODBINE SAND.

The Woodbine sand, named from the village of Woodbine, in Cooke County, is the basal division of the Gulf series in northeastern Texas. It is a highly variable formation, consisting of strongly current-bedded, more or less ferruginous sand and laminated shaly clay, with some interbedded layers of lignite and lignitic clay. On account of the irregularity of the bedding it is scarcely possible to determine the thickness of the formation from surface outcrops, but it is reasonably certain that in Grayson County the thickness is not less than 300 or 400 feet and may be as great as 500 feet. A well at Ladonia, in the southeast corner of Fannin County, penetrated between depths of 1,800 and 2,425 feet about 625 feet of sand and clay which are interpreted as belonging to the Woodbine. As stated above, the Woodbine becomes progressively thinner toward the south, finally disappearing in McLennan County. The formation is traceable eastward from Grayson County through Texas and into Arkansas, where it is believed to be represented by a part at least of the Bingen sand.

The scope of this paper will not permit a detailed account of the many different lithologic aspects of the formation, for which the reader is referred to the sections described by Hill and Taff in the papers listed on pages 130–131. Hill recognized two subdivisions of the Woodbine—a lower member, called by him the Dexter sands, consisting of an estimated thickness of 160 feet of "brown and yellow ferruginous sandstone heavily laden with siliceous ironstone," and an upper member, called by him the Lewisville beds, consisting of 150 feet or more of "laminated lignitic sands and sandy clays, interstratified with brown sands, ferruginous reddish-brown sandstone, shell sandstone, and argillaceous shelly sandstone which contains large lenslike calcareous concretions and laminated argillaceous sandstones at the top." Sand seems to predominate over clay, producing a pronounced sand-hill type of topography, as in the country immediately southwest and west of Denison; but locally clay makes up the bulk of the formation, producing a smoothly rolling surface, as in the belt of country northwest of Pottsboro. (See p. 132.)

Fossil leaves have been obtained from the lower member (Hill's Dexter sands) of the Woodbine near Denison. The upper member (Hill's Lewisville beds) yields a peculiar shallow marine fauna that differs markedly from the Cretaceous faunas either below or above it in Texas. This fauna is best known from exposures on Timber Creek, 3 or 4 miles west, southwest, and south of Lewisville, Denton County, Tex., and though it includes a relatively small number of species is rich in individuals, which largely make up certain lenses and layers of the formation. The following are some of the species that have been described:

Arca (Barbatia) micronema (Meek), numerous.
Ostrea soleniscus Meek, very numerous.
Modiolus filisculptus Cragin.
Cytherea leveretti Cragin.
Cerithium tramatensis Cragin.
Cerithium interlineatum Cragin

The fossiliferous strata of the upper member are represented in Grayson County, though they are not so conspicuously exposed as they are on Timber Creek in Denton County.

Fossil plants have also been collected from beds regarded as representing the Woodbine formation at Arthurs Bluff, on Red River 15 miles north of Paris, in Lamar County, Tex.

The Woodbine sand outcrops in a belt a few miles wide along the south limb of the Preston anticline (see geologic map, Pl. XVII) and in a north-south belt along the western border of the area mapped. The belt of outcrop wraps around the southeastward-plunging nose of the Preston anticline in northwestern Fannin County, Tex., and passes northward into Oklahoma, where it extends in a broad belt to the northwest and north, and to the east down the Red River valley. Exposures of the Woodbine at three localities are shown in Plates XXIV, *A*, and XXV, *A* and *B*.

The formation may be studied to advantage on sandy hills along the northern margin of the belt of outcrop between Pottsboro and Cedar Mills, in Grayson County; in road and railroad cuts and creek beds between Denison and Pottsboro, and for several miles southwest of Denison; in cuts of the Missouri, Kansas & Texas Railway in the western outskirts of Denison, Grayson County (see Pl. XXIV, *A*); in roads and stream banks and beds in the hilly country within 6 or 7 miles east-southeast of Denison; on sandy hills in the northwestern part of Fannin County; and at Hyatts Bluff, on Red River just above the mouth of Caney Creek, 6 miles northwest of Ravenna, Fannin County (Pl. XXV, *A*).

Hyatts Bluff, not heretofore described, is half a mile long and 45 feet high and trends N. 28° E. Reddish terrace sand forms the upper 20 feet of the section, beneath which are 25 feet of Woodbine strata consisting of soft cross-bedded glauconitic sandstone; dark-greenish, more massive soft glauconitic sandstone; small lenses of pebbly sand; and dark shaly clay. The main bedding planes are fairly persistent and dip perceptibly downstream. One persistent sandstone stratum 2½ feet thick, overlain by a lignitic band a foot thick, was traced from a point where it is 20 feet above water level for 1,800 feet along the face of the bluff to a point where it passes beneath water level. The dark shaly clay forming the portion of the section that is stratigraphically highest in the Woodbine contains concretions of iron carbonate, some of which are fossiliferous, and there is one layer of dark-greenish glauconitic soft sandstone containing the abundant remains of a poorly preserved molluscan fauna that inhabited a shallow sea. The photograph reproduced in Plate XXV, *A*, was taken where the lignitic band lies at water level and is overlain by 4 or 5 feet of shaly, easily eroded clay. The conspicuous projecting ledge is highly cross-bedded sandstone along the base of which are discontinuous small lenses of conglomerate.

EAGLE FORD CLAY.

The Woodbine sand is overlain by the Eagle Ford clay, a formation named from Eagle Ford, a village 6 miles west of Dallas, where it is typically exposed. The formation consists chiefly of dark bluish-gray to nearly black shaly clay which is as a rule gypsiferous and more or less bituminous; in places crystals of selenite weather from the clay in great numbers. In Grayson and Fannin counties the formation has an estimated thickness between 300 and 400 feet. Thin, platy layers of sandstone and sandy limestone, some bearing the imprints of small costate and keeled ammonites, occur in the formation, particularly in the central portion. Flattish calcareous nodules occur in the lower part of the formation, and oval to spherical hard limestone septaria are characteristic of the upper part. In the upper 20 or 25 feet of the formation in the vicinity of Sherman the dark clays are interstratified with beds of sand, one of which, 15 to 20 feet below the base of the Austin chalk, carries vast numbers of the small fluted oyster, *Ostrea lugubris* Conrad. Ten feet below the base of the Austin chalk, which in Grayson County overlies the Eagle Ford, is a conglomeratic layer of gray sandstone, carrying numerous more or less rounded phosphatic pebbles, shells of *Ostrea alifera* Cragin, and fish teeth, of which shark teeth are common. This is the "fish-bed conglomerate" of Taff,[1] which in the opinion of the present writer (see p. 149) should not be included in the Eagle Ford but should be regarded as the base of the sediments that have their typical expression in the Austin chalk.

The formation outcrops in an east-west belt through the northern part of Grayson County and the northwestern part of Fannin County, but the belt is sharply deflected to the south in northwestern Fannin County, where it passes around the southeast end of the Preston anticline. In the northern part of Fannin County the formation passes under the Pleistocene terrace deposits of the Red River valley; east of Fannin County the only place where it has been certainly recognized in surface outcrops is Garretts Bluff, in the northwestern part of Lamar County. Two localities where the formation can be advantageously studied in northern Fannin County are at Sowells Bluff, on Red River 5 miles northwest of Ivanhoe, and in deep ravines in the westward-facing slope of the Red River valley 6 miles north of Ivanhoe. At the last-named locality, where approximately 140 feet of strata are exposed, the upper part of the section exhibits a larger proportion of sandstone than is typical of the formation, and some beds of the sandstone are cross-bedded, simulating the Woodbine sand. Below this dominantly sandy portion, 40 or 50 feet below the top of the section, is a gravel layer generally less than a foot thick, composed chiefly of dark, smooth pebbles which have not yet been critically studied. This may represent the "fish-bed conglomerate," in which case both the pebble layer and the beds above it, including the dominantly sandy strata, should, in the writer's opinion, be excluded from the Eagle Ford formation. Characteristic Eagle Ford fossils have been obtained from wells in northeastern Louisiana.[1]

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[1] Texas Geol. Survey Fourth Ann. Rept., for 1892, pp. 299-304, 1893.

West of Sherman and Denison the belt of outcrop bends nearly due south and is traceable through Texas to the Rio Grande, which it intercepts in Kinney and Valverde counties. Well records show the formation to be 535 feet thick in the western part of Collin County, Tex., and 460 to 485 feet in the vicinity of Dallas; south of Dallas it becomes thinner, reaching a minimum of about 30 feet at Austin; southwestward and westward from Austin the thickness again increases, being 75 feet or more in the Uvalde quadrangle and about 250 feet in the Brackett quadrangle.

The sandy beds at the top of the Eagle Ford have been traced from the vicinity of Sherman eastward through Grayson County and northeastward to about the north-central part of Fannin County. Good exposures of the sandy beds occur in the vicinity of Bells in eastern Grayson County. A mile west of Bells the east-west public road that runs about a quarter of a mile south of the Texas & Pacific Railway crosses a layer of ferruginous sandstone at the head of a northward-flowing branch of Mill Creek, which probably represents the "fish-bed conglomerate." (See p. 146.) The sandstone is underlain by 4 or 5 feet of dark greenish-gray massive sand, and in succession down the ravine follow 35 or 40 feet of more or less argillaceous fine sand, with layers of soft yellow sandstone at intervals, and about 40 feet of dark shaly gypsiferous septaria-bearing clay, typical of the Eagle Ford clay.

Another good exposure of the sandstone layer ("fish-bed conglomerate") occurs in an east-west public road on the westward-facing slope of the Mill Creek valley 2 miles in an air line southwest of Bells, where it is underlain by 15 or 20 feet of fine gray massive marine sand. The base of the Austin chalk appears at a higher level in the same road a short distance east of the outcropping ledge of sandstone, from which it is separated by 10 or 15 feet of poorly exposed strata, apparently clay.

From the vicinity of Bells eastward these upper sandy beds of the Eagle Ford have produced a narrow belt of country characterized by sandy soil and rougher topography than that exhibited by the adjacent land either to the north or to the south. Outcrops of the persistent "fish-bed conglomerate" occur here and there just above the sand and serve as a check to the correlation of this sandy member of the Eagle Ford, which crosses the headwaters of Caney Creek 2½ miles southeast of Bells and, approximately paralleling this creek, swings around the plunging nose of the Preston anticline and extends to the northeast past Lesleys schoolhouse, Ector, and Ravenna, in Fannin County. The "fish-bed conglomerate" is more fully described on pages 148–149.

The upper part of the Eagle Ford formation is exposed in a branch west of a north-south road and south of an east-west portion of the same road 3 miles south of Ravenna. Immediately below the conglomerate at the locality shown in Plate XXVII, *B*, is 5 feet of fine argillaceous marine sand, near the top of which was observed a large piece of lignite. Within about a quarter of a mile farther down the branch occur good exposures of typical dark shaly gypsiferous clay of the Eagle Ford formation; interbedded with this clay are subordinate layers of fine-grained sandstone and a few layers and lenses of gray calcareous earthy rock that exhibits finely developed cone-in-cone structure. In places thick layers of this earthy rock surround apparently concretionary masses of limestone. Several specimens of *Ostrea lugubris* Conrad were found loose in the bed of the creek below the outcrop of the conglomerate and probably came from some bed in the upper part of the Eagle Ford.

Some of the common fossils of use in recognizing the Eagle Ford formation are *Ostrea lugubris* Conrad, *O. alifera* Cragin, fish teeth belonging to the species *Ptychodus whipplei* Marcou, *Inoceramus labiatus* Schlotheim, *I. fragilis* Hall and Meek, and small keeled ammonites belonging to *Prionotropis* or *Prionocyclus*, or to both. Of these the first three occur only in the upper 40 or 50 feet of the formation.

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[1] Matson, G. C., The De Soto-Red River oil and gas field, La.: U. S. Geol. Survey Bull. 661, p. 115, 1917.

AUSTIN CHALK.

TYPICAL AREA.

The Austin chalk is typically exposed in the vicinity of Austin, Travis County, Tex., where it rests upon the Eagle Ford clay, is approximately 410 feet thick, and consists of white chalky limestone in beds of varying thickness, with interbedded marly layers in its upper two-fifths. Some of the common fossils that are especially characteristic of the formation are the following:

Inoceramus undulato-plicatus Roemer.
Ostrea aff. O. diluviana Lamarck (uppermost part).
Gryphaea aucella Roemer.
Exogyra ponderosa Roemer (upper half).
Exogyra laeviuscula Roemer (upper half).
Radiolites austinensis Roemer.
Mortoniceras texanus (Roemer).

The Austin chalk extends from the Rio Grande in Maverick County, Tex., eastward by way of Uvalde to San Antonio, thence northeastward to Austin, and thence northward by way of Waco and Austin to Grayson County. From Austin northward the chalk thickens, and its upper surface appears gradually to transgress upward across the geologic column, or, in other words, to become younger, until in the latitude of Sherman the uppermost bed of chalk is considerably younger than the top of the chalk at Austin and occupies a position stratigraphically 400 or 500 feet higher. The exact manner in which this upward transgression takes place, whether by a gradual rise or by minor tongues of chalk at successively higher positions, has not been determined, very little detailed field work having been done in the intervening area.

DEVELOPMENT IN NORTHEASTERN TEXAS.

SALIENT FEATURES.

In the Sherman-Greenville section the Austin chalk is probably not less than 1,000 feet thick. In the eastern part of Grayson County and the western part of Fannin County, however, the lower two-fifths or more of the chalk becomes impure and gradually passes laterally into nonchalky sands and clays and only slightly chalky clay marls. In a section drawn through Bonham, Fannin County, and Commerce, Hunt County, the succession of recognizable and mappable lithologic units is decidedly different from that in the latitude of Austin. In Collin, Hunt, and Delta counties other lithologic changes have taken place in beds above the chalk, representing the upper part of the Taylor marl, and these changes add further contrast to the section in northeastern Texas as compared to that in the Austin region. These relations are diagrammatically shown in Plate XXX, *C*.

In the Bonham-Commerce section the following divisions, named in ascending order, together represent the chalk and its equivalents in this area: A band of basal nonchalky clay and sand 10 to 35 feet thick, with the "fish-bed conglomerate" described below, at its base, all mapped with the Ector tongue; the Ector tongue of the Austin chalk; an unnamed transitional clay in the vicinity of Bonham (p. 150); and the Annona tongue of the Austin chalk. (See Pl. XXX, *C*.)

In the longitude of Paris, Lamar County, the chalk and its equivalents include imperfectly known beds, probably clay, sand, and marl, representing the eastward extension of the Ector tongue and part of the clay in the vicinity of Bonham; the Blossom sand; the Brownstown marl; and the Annona tongue of the Austin chalk. (See Pl. XXX, *C*.)

UNNAMED CLAYS AND SANDS CONTEMPORANEOUS WITH BASAL PART OF TYPICAL AUSTIN CHALK.

Phosphatic pebbles occur in the base of the Austin chalk, immediately above its contact with the underlying Eagle Ford formation, in a quarry of the Texas Portland Cement Co., 3 miles west of Dallas, Tex. (See Pl. XXVII, *A*.) In Grayson County, Tex., a conglomeratic layer, a few inches to 30 inches thick, called by Taff[1] the "fish-bed conglomerate," occurs 10 feet below the base of the chalk, with beds of shaly clay and sand intervening. From Grayson County the conglomerate extends eastward into Fannin County, where from west to east the interval between the conglomerate and the base of the overlying chalk, which is here the Ector tongue of the Austin, gradually increases until in the vicinity of Ector and Ravenna it is not less than 35 feet. Between Ector and Ravenna, in Fannin County, the material in this interval is mostly greenish cal-

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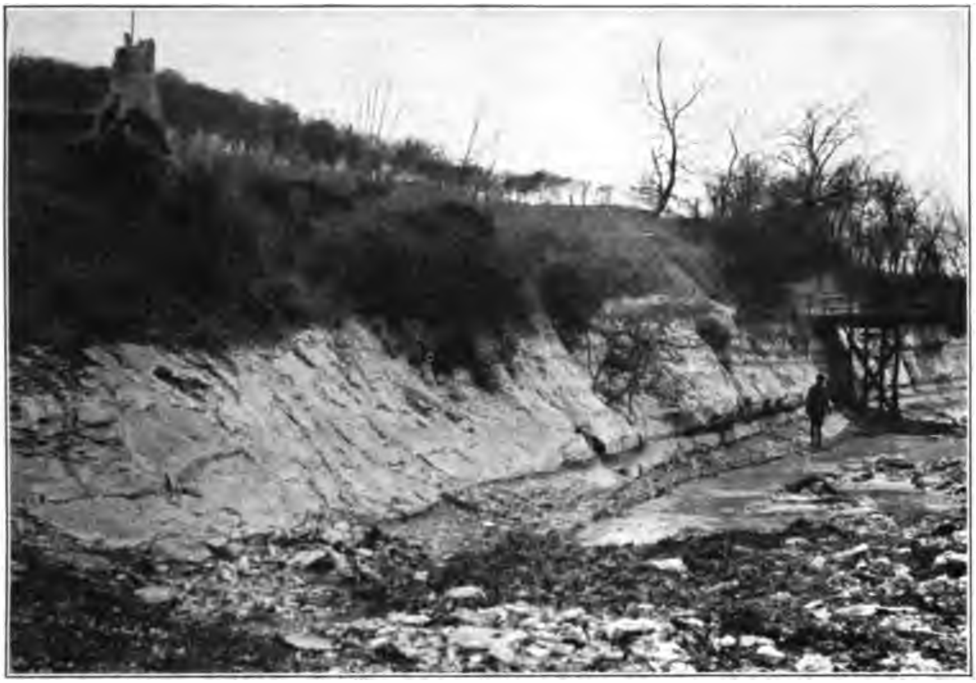
[1] Texas Geol. Survey Fourth Ann. Rept., pp. 303, 304, 1893.



A. ANNONA TONGUE OF AUSTIN CHALK IN THE BANK OF A CREEK 5½ MILES WEST OF LEONARD, FANNIN COUNTY, TEX.

The beds, which dip perceptibly downstream, comprise massive layers of chalk interbedded with shaly layers 6 inches to 2 feet thick.

B. BUILDING-STONE FACIES AT TOP OF ANNONA TONGUE OF AUSTIN CHALK IN AN ABANDONED QUARRY 3 MILES SOUTH OF HONEY GROVE, FANNIN COUNTY, TEX.

careous shaly clay becoming more or less sandy, with lenses of sand and sandstone in the lower 10 feet. Lithologically the clay is of lighter color than the typical clay of the Eagle Ford.

The "fish-bed conglomerate" is well exposed in a branch west of a north-south public road 3 miles south of Ravenna, where it forms a ledge across the bed of the stream. (See Pl. XXVII, *B*.) At this place it consists of a conglomeratic layer about 10 inches thick composed of coarse calcareous sand, grayish and brownish phosphatic pebbles, a few pebbles of quartz and chert, and scattered shark teeth. One specimen of *Ostrea alifera* Cragin was obtained from the conglomerate at another outcrop in an east-west road about a quarter of a mile northwest of this locality, where also a thin interbedded layer of earthy limestone exhibiting cone-in-cone structure was noted. One pebble from the conglomerate was examined qualitatively by W. B. Hicks in the chemical laboratory of the United States Geological Survey and found to be composed chiefly of calcium phosphate. The conglomerate is here about 35 feet below the base of the Ector tongue of the Austin chalk (see Pl. XXX, *C*), and apparently the intervening strata are chiefly greenish shaly clay.

A gravel bed that may represent the northeastward continuation from the preceding locality of the "fish-bed conglomerate" is described on pages 146–147.

The significance of the "fish-bed conglomerate" in the geologic history of this part of Texas has not been definitely determined. Heretofore the conglomerate, together with the 10 to 35 feet of clay and sand that intervene between it and the overlying chalk, have been regarded as forming the uppermost part of the Eagle Ford. The conglomerate, lying immediately above sandy beds that are obviously of shallow-water marine origin, strongly suggests a temporary uplift of the sea bottom of this area above sea level, followed soon after by a readvance of the sea and the formation of the pebble bed as a basal conglomerate marking the beginning of the cycle of deposition that has its typical expression in the Austin chalk. This interpretation, if found to be correct, would seem to necessitate the exclusion of the conglomerate and the overlying clay and sand from the Eagle Ford. Such Eagle Ford fossils as the conglomerate may be found to contain can be explained as having been mechanically introduced from underlying Eagle Ford strata in place.

ECTOR TONGUE.

The Ector tongue of the Austin chalk, a thin tonguelike projection of chalk from the basal beds of the main body of the Austin, has been traced, by means of a few outcrops and the black soils to which the chalk weathers, from western Fannin County northeastward to a point about a mile and a half southeast of Ravenna. (See Pl. XVII.) Ector, from which the tongue is named, is a few hundred yards west of the belt of outcrop, which is rather strongly deflected where it passes around the southeastern nose of the Preston anticline. Only 10 or 15 feet of the chalk was seen in the best exposures, and it probably does not exceed 50 feet in thickness in the vicinity of Ector. The Ector tongue is underlain by shaly clay, which apparently grades into the chalk through a thickness of only a foot or two of material. This clay, together with thin beds of sand and a basal conglomerate ("fish-bed conglomerate") associated with it, are regarded as distinct from the Eagle Ford formation and as more closely related in origin to the overlying Austin chalk and its equivalents. (See above.) These basal beds are mapped with the Austin chalk and its extension, the Ector tongue. No exposures of the Ector tongue showing clearly its relation to the clay of Austin age that overlies it were seen.

The chalk is poorly exposed in the public road north of the Texas & Pacific Railway about a quarter of a mile east of Ector.

Another exposure appears in an east-west public road about 3 miles north by east of Ector, or 5¼ miles northwest of Bonham; here several feet of the chalk is underlain by clay, the passage from the clay to the chalk apparently being transitional through a thickness of a foot or more of material.

In other exposures revealed by a small branch and gullies west of a north-south public road 3 miles south of Ravenna the weathered rock has the appearance of typical chalk of the Austin and yielded the characteristic fossils *Gryphaea aucella* Roemer and *Radiolites austinensis* Roemer. As noted above, the "fish-bed conglomerate" crops out in the bed of the branch and in an east-west public road less than a quarter of a mile west of this locality, in a position about 35 feet stratigraphically lower than the base of the chalk.

The belt of chalk of the Ector tongue crosses the old Bonham-Ravenna road about 1½ miles southeast of Ravenna, where the chalk was seen in a small, poor exposure in the road ditch. This is the easternmost locality at which this chalk has been recognized, and its identification farther east would probably be accomplished with difficulty, owing to the extensive covering of Pleistocene alluvial deposits in a broad belt south of Red River in Fannin and Lamar counties. It is assumed for the present that the chalk loses its identity toward the east by merging into contemporaneous nonchalky clays or sands.

The structure contours in the vicinity of Savoy, Ector, and Ravenna shown in Plate XVII indicate the altitude above sea level of the base of the Ector tongue.

TRANSITIONAL CLAYS NEAR BONHAM.

The Ector tongue of the Austin chalk is overlain in the west-central part of Fannin County by greenish-gray waxy clay, weathering yellowish green, which in the Bonham region appears to occupy the entire interval of approximately 400 feet above the Ector tongue and below the Annona tongue of the Austin. Exposures of the clay appear in roads and streets both north and south of Bonham and in the ditches of the roads leading to the north, northwest, west, and southwest. As considerable areas bordering Bois d'Arc Creek are covered by terrace clay derived chiefly from the underlying Cretaceous clay, it is in places difficult to determine whether the more or less weathered materials are residual from the undisturbed older clay or from the reworked terrace deposits.

A little above the middle of this body of clay is a band of glauconitic clay, of undetermined thickness, that is lithologically identical with pockets or lenses of glauconitic clay in the Blossom sand near Paris, Lamar County. This band has been recognized in poor exposures in street ditches south of the railroad in Bonham, and in somewhat better exposures on the Randolph road 5 and 6½ miles by the road southwest of Bonham. At the last-mentioned locality the clay is calcareous and strongly glauconitic and contains fragments of a large species of *Inoceramus*, *Ostrea congesta* Conrad, and *Ostrea plumosa* Morton. These fossils, though in themselves not conclusive evidence, combined with the lithologic evidence mentioned above indicate that the glauconitic clay represents the Blossom sand. A layer of impure sandy limestone exposed in a small branch at the crossing of the road to Prospect Church, 3 miles northwest of Dodd City, Fannin County, yielded *Aguilaria?*, *Inoceramus* sp., *Ostrea plumosa* Morton, *Gryphaea aucella* Roemer, *Baculites asper* Morton, and *Prionotropis?*. These fossils indicate that this locality also lies within the belt of clay representing the Blossom sand.

The upper part of the clay in the vicinity of Bonham above the glauconitic band is greenish and waxy and contains a few calcareous septaria; it represents the Brownstown marl, which, in the vicinity of Paris, lies above the Blossom sand and below the Annona tongue of the Austin chalk. (See Pl. XXX, *C*.)

In Plate XXX, *C*, the clay in the vicinity of Bonham is represented as merging toward the west through calcareous clay into the Austin chalk. That this interpretation is correct, and that the merging takes place gradually through a considerable linear distance, appears to be confirmed by all the observations that have been made in the area. On the strike of the clay in the area between Bells and Whitewright, in eastern Grayson County, the rock underlying the surface is composed largely of impure argillaceous chalk and chalky clay that appear to be transitional, and even as far west as the vicinity of Luella, in the east-central part of Grayson County, a considerable thickness of the Austin is a highly argillaceous, slightly bituminous shaly chalk or chalky clay. This facies of the Austin is exposed in gullies in the small branches of Cedar Creek near Luella and in the northward-flowing branches and northward-facing slopes of Choctaw Creek north of Luella.

The lower part of the clay in the vicinity of Bonham has not been traced farther east than the central part of Fannin County, beyond which in northeastern Fannin and northern Lamar counties the strata are largely obscured by an extensive covering of Pleistocene alluvial terrace deposits and are therefore imperfectly known. However, the distribution and relations of the clay seem to indicate that either it or equivalent material that is lithologically different, such as sand or marl, extends eastward stratigraphically beneath the Blossom sand. (See Pl. XXX, *C*.)

ANNONA TONGUE.

The division to which the name Annona is now applied was originally called the "White Cliffs chalk" by Hill,[1] from White Cliffs village and bluff, on Little River, Little River County, Ark. Because "White Cliffs" was preoccupied as a formation name, Hill, in 1901,[2] renamed the chalk Annona, from the town of Annona, in Red River County, Tex. The new name was inappropriate, for Annona is several miles south of the belt of outcrop of the chalk, but the name has become so commonly used that it should be retained, with the understanding, however, that the chalk does not outcrop at Annona—in fact, the section at White Cliffs, Ark., should continue to be regarded as the type locality of the division.

Hill[3] regarded the Annona as stratigraphically higher than the Austin as developed in its type area, for he says:

> It is not known what has become of the Austin chalk in this section [Paris, Tex.], but my hypothesis, backed by some evidence, is that to the southward it has been faulted down. The Anona (White Cliffs) is an entirely distinct and higher bed, for it is underlain by the Taylor (*Exogyru ponderosa*) marls, which overlie the Austin chalk.

In a later report[2] he says:

> The chalky (Anona) beds (the White Cliffs chalk of the writer's Arkansas section) outcrop at Clarksville and thence via Paxton [Roxton] and Honey Grove nearly to Bonham but are not known south of these points. The writer has considered this chalk to represent a higher horizon than the Austin chalk, but its exact relationship is subject to future determination.

Outcrops of chalk north of Windom and Honey Grove, in Fannin County, which in reality lie within the belt of outcrop of the Annona, were regarded by Hill[4] as belonging to the Austin.

Taff[5] recognized the geographic continuity of the Austin and Annona and also the fact that the lower part of the Austin is represented in northeastern Texas by beds that are not typical chalk. He says:

> The lower part of the thick chalk formation of north Texas changes to marl in the vicinity of Sherman, and still farther east higher beds successively become chalky marl, so that within a comparatively short distance only the upper part of the chalk formation as it occurs farther south is true chalk. In other words, the white chalk transgresses upward in the series of Cretaceous rocks from the vicinity of Sherman, Tex., eastward into Arkansas.

It is not quite clear from this quotation whether Taff regarded the Annona as actually younger than the upper part of the type Austin, or whether the last sentence of the quotation refers only to an upward transgression of the base of the chalk.

Gordon[6] also recognized the continuity of the Austin and Annona but did not detect the upward transgression of the top of the chalk across the geologic column from Austin northward. He therefore combined the Annona chalk and underlying Brownstown marl under the name Austin group, which he represented as occupying the time interval of the typical Austin of central Texas.

The Annona tongue in northeastern Texas consists of 400 or 450 feet of bluish-gray brittle, more or less argillaceous chalk, which breaks with a conchoidal fracture and weathers to white bald spots such as are typical of the area farther south in Texas underlain by the main body of the Austin chalk. The chalk is slightly bituminous, fresh samples from practically any part of it having a decided bituminous odor when struck with the hammer and yielding small quantities of oil by destructive distillation. The Annona has been traced almost continuously from a point north of Annona, in Red River County, through Lamar and Fannin counties to the southwestern part of Fannin County, where it is found to be continuous with the upper part of the main body of the Austin chalk (see Pl. XVII and Pl. XXX, *C*), and for that reason it is here regarded as a tongue of the Austin formation. No good exposure was found showing the relation of the Annona tongue to the underlying Brownstown marl, into which, however, the chalk probably merges through a vertical transition zone.

The upper 5 to 10 feet of the Annona in parts of northeast Texas consists of soft, tough, uniform chalk, which weathers to a soft cream color and is capable of being readily sawed into building blocks. It has been used locally in the construction of foundations, chimneys, dwellings, stores, churches, and courthouses.

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[1] Arkansas Geol. Survey Ann. Rept. for 1888, vol. 2, pp. 87–89, 1888.

[2] U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, p. 341, 1901.

[3] Geol. Soc. America Bull., vol. 5, p. 308, 1894.

[4] U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, pl. 66, 1901.

[5] U. S. Geol. Survey Twenty-second Ann. Rept., pt. 3, pp. 698–699, fig. 58, 1902.

[6] Gordon, C. H., U. S. Geol. Survey Water-Supply Paper 276 pp. 21–25, 1911.

As a building stone, this rock appears to be durable and is of pleasing appearance; in its toughness and lack of brittleness the rock is in strong contrast to the chalk immediately underlying it and to the ordinary chalks of the Cretaceous formations of the Gulf Coastal Plain. The building-stone faciès appears to be rather sharply separated from the overlying Taylor marl and forms a persistent stratum that has been traced from a point south of Atlas, in Lamar County, to Bailey, in Fannin County. It was not seen in the vicinity of Leonard, Fannin County, but rock of apparently identical physical character crops out on the hills 4 miles east of McKinney, in Collin County, where it has been quarried for building stone, and similar rock has also been quarried about 4 miles east of Allen, Collin County.

About 13 miles east of Clarksville the Annona passes under the alluvium of Red River, beneath which it is concealed to the Arkansas boundary, but the chalk reappears at Rocky Comfort, in the southwestern part of Little River County, Ark., and again at White Cliffs, on Little River in the same county. It passes as a narrow belt through the southeastern part of Howard County and thins and disappears in the western part of Hempstead County.

The set of structure contours on the geologic map (Pl. XVII), extending from the area north of Honey Grove southwest by west to Randolph, Fannin County, indicates the altitude above sea level of the sloping base of the Annona tongue of the Austin chalk; the broad eastward deflection of these lines south of Bonham marks the eastward extension of the plunging nose of the Preston anticline. The set of contours extending from the area south of Honey Grove, southwest by west past Gober and Bailey to Leonard, Collin County, indicates the altitude of the top of the Annona tongue; the slight eastward deflection of these lines northeast of Gober probably approximately marks the dying out of the uplift that produced the Preston anticline. The somewhat more pronounced southward deflection of these same contour lines at Leonard marks another structural feature that is described on page 161 as the Leonard-Celeste monoclinal fold.

BLOSSOM SAND.

The sand to which the name Blossom is applied was first recognized by Veatch[1] in wells at Clarksville, Red River County, where it constitutes an important water-bearing formation; he called it the "sub-Clarksville sand." Gordon[2] renamed the sand the Blossom sand member of the Eagle Ford clay, correlating it especially with the sandy beds that form the upper part of the Eagle Ford in the vicinity of Sherman, in Grayson County, an interpretation which, as shown by the abundant evidence presented in this paper, is incorrect.

The Blossom sand, which Gordon described as "brown sandy ferruginous glauconitic beds interlaminated with thin beds of clay, is overlain by the Brownstown marl and forms a belt of sandy country several miles wide extending westward through Red River County north of Clarksville; thence westward through Lamar County, where Blossom and Paris are on the outcrop; thence westward into Fannin County, where north of Dodd City it merges into clay (see Pl. XXX, *C*), changing its topographic and much of its lithologic character. However, the clay into which it merges toward the west retains its characteristic glauconitic content and is traceable past the south side of Bonham to a point about halfway between Ector and Randolph. Some facies of the sand are strongly calcareous and are chalky in appearance.

Fossil evidence indicates that the Blossom sand corresponds in age to the upper part, perhaps the upper half, of the Austin chalk as developed in the type area in Travis County. The fossils listed in the table below have been collected at a sufficient number of localities between Blossom, in Lamar County, and a point southwest of Bonham, in Fannin County, to amount to a virtual tracing of the beds throughout this distance of about 50 miles. At least eleven of the species are common to the Austin chalk of the type area, whereas no Eagle Ford species appear in the list. Synchroneity with the upper part of the type Austin is especially indicated by the following forms: *Inoceramus* aff. *I. deformis* Meek, *Ostrea congesta* Conrad, *Ostrea* aff. *O. diluviana* Linné, *Gryphaea aucella* Roemer, *Exogyra ponderosa* Roemer, *Liopistha elegantula* (Roemer)? and *Baculites asper* Morton.

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[1] Veatch, A. C., Geology and underground water resources of northern Louisiana and southern Arkansas: U. S. Geol. Survey Prof. Paper 46, p. 25, 1906.

[2] Gordon, C. H., Geology and underground waters of northeastern Texas: U. S. Geol. Survey Water-Supply Paper 276, p. 19, 1911.

The paleontologic evidence that the Blossom sand is younger than the Eagle Ford is supplemented by the lithologic evidence, for hand specimens of glauconitic clay collected on the Randolph road 5 to 6½ miles southwest of Bonham, Fannin County, in a bed that is stratigraphically well above the top of the Eagle Ford, are identical in physical aspect with specimens from undoubted Blossom sand near Paris, Lamar County.

Fossil species from the Blossom sand in Fannin, Lamar, and Red River counties, Tex.

Species.	Blossom sand.								Sandy limestone of Blossom age.	Clay of Blossom age.	Species common to the Austin chalk of the type area.
	U. S. Geological Survey collection 7496; 5 miles north by west of Clarksville, Red River County.	U. S. Geological Survey collection 9704; 2¼ miles west by south of Blossom.	U. S. Geological Survey collection 9703; 2¼ miles east by south of Paris.	U. S. Geological Survey collection 9702; 1½ miles west by south of public square, Paris.	U. S. Geological Survey collection 7508; 1¼ miles south by west of public square, Paris.	U. S. Geological Survey collection 9707; near Hopewell, 6 miles northwest of Paris.	U. S. Geological Survey collection 9701; Forest Hill Church, 7 miles northeast of Honey Grove.	U. S. Geological Survey collection 9699; Lone Elm Church, 7 miles northwest of Honey Grove.	U. S. Geological Survey collection 9695; 3 miles north by west of Dodd City.	U. S. Geological Survey collection 9693; 5¼ miles southwest of Bonham.	
Vermes:											
Serpula sp			×		×		×				
Mollusca:											
Nucula sp					×						
Cucullaea sp				×			×	×			?
Arca?								×			
Glycymeris?	×			×							
Aguileria?				×					×		
Pteria?					×						
Inoceramus aff. I. deformis Meek					×			×			×
Inoceramus sp. (1)									×		×
Inoceramus sp. (2)	×					×				×	
Ostrea congesta Conrad			×		×	×		×		×	×
Ostrea plumosa Morton			×		×				×	×	×
Ostrea aff. O. diluviana Linné					×						×
Gryphaea aucella Roemer					×	×		×	×		×
Exogyra ponderosa Roemer		×	×	×	×						×
Trigonia sp					×		×				
Pecten quinquecostatus Sowerby				×	×			×			×
Pecten sp					×						
Lima sp				×	×			×			
Spondylus sp								×			
Clavagella sp					×						
Liopistha elegantula (Roemer)?				×							×
Veniella sp					×						
Cardium spillmani Conrad	×										×
Cardium (Criocardium) sp	×				×						
Cardium sp			×	×	×		×				
Cyclorisma sp	×										
Xenophora sp					×		×				
Gyrodes sp								×			
Volutoderma sp			×		×		×	×			
Anisomyon sp					×						
Nautilus sp				×							
Hamites sp				×	×						
Baculites asper Morton			?	×	×		?	×	×		×
Placenticeras sp				×							
Prionotropis?									×		
Vertebrata (fish):											
Corax falcatus Agassiz				×							?
Otodus sp			×								

BROWNSTOWN MARL.

The Brownstown marl in its type area in Arkansas[1] consists of about 600 feet (?) of blue or gray calcareous clay or marl lying above the Bingen sand and below the Annona tongue of the Austin chalk. In northeastern Texas the Brownstown overlies the Blossom sand and underlies the Annona tongue, but its thickness probably does not exceed 300 or 350 feet. In Texas the marl resembles in a general way that of the type area, though some of it consists of gray waxy clay that is only slightly calcareous. Calcareous septaria have been observed in the clay in places in Lamar and Fannin counties. In general the soils produced by the Brownstown are of gray aspect and are in fairly strong contrast to the deep black soils of the Annona chalk on the south. The Brownstown marl extends westward, merging into the upper part of the clay in the vicinity of Bonham, Fannin County, and this clay in turn merges toward the west into the Austin chalk, as described on page 150.

The paleontologic character of the Brownstown marl has been only superficially studied. Probably the most common fossil species other than those of microscopic size is *Exogyra ponderosa* Roemer, which is very abundant in places in Texas and Arkansas. The following species have been recognized in the formation in Arkansas:

Hamulus major Gabb.
Hamulus onyx Morton.
Ostrea plumosa Morton.
Exogyra ponderosa Roemer.
Anomia argentaria Morton.
Paranomia scabra (Morton).
Liopistha (Cymella) bella (Conrad)?
Crassatellites conradi (Whitfield)?
Cyprimeria depressa (Conrad).
Corbula crassiplica Gabb.
Turritella quadrilira Johnson.
Baculites asper Morton.

When the Upper Cretaceous section of northeastern Texas is compared with that of Colorado River in Travis County near Austin it appears that the Brownstown marl is the equivalent in age of the lower part of the Taylor marl. This relation is indicated by red line *c* in Plate XXX, *C*.

TAYLOR MARL.

TYPICAL AREA.

The Taylor marl is typically developed in the vicinity of Taylor, Williamson County, and in Travis County, Tex., where it consists of 540 feet or more of "bluish unctuous marly clay which weathers into yellow laminated subsoil and black surface soil."[2] The formation conformably overlies the Austin chalk and is in turn conformably overlain by the Navarro formation. The most common and conspicuous fossil in the Taylor is *Exogyra ponderosa* Roemer, which is particularly abundant in the lower part of the formation but which is also common in places in the upper part of the formation.

DEVELOPMENT IN NORTHEASTERN TEXAS.

SALIENT FEATURES.

The Taylor marl of northeastern Texas occupies the interval between the underlying Annona tongue of the Austin chalk and the overlying Navarro formation and has an estimated thickness of 500 to 600 feet of strata. The correlation diagram (Pl. XXX, *C*) shows that the Taylor of this area represents only the upper part, perhaps not more than the upper half, of the formation as developed in its type area in Williamson and Travis counties. This difference in the time limits of the formation is due to the upward transgression of the top of the Austin from Travis County northward. Approximately the lower 475 feet of the Taylor as developed in Fannin and Hunt counties consists mainly of gray or bluish-gray calcareous shaly clay or marl, some portions of which are finely sandy; these deposits are of similar lithologic character to the typical Taylor marl of central Texas.

The basal part of the Marlbrook marl of southwestern Arkansas, which rests upon the Annona chalk and contains *Exogyra ponderosa* Roemer, probably corresponds to at least a part of the Taylor marl of northeastern Texas. The upper part of the Marlbrook, which carries *Exogyra cancellata* Stephenson, though perhaps continuous with the Taylor, is younger than the Taylor and corresponds in age with

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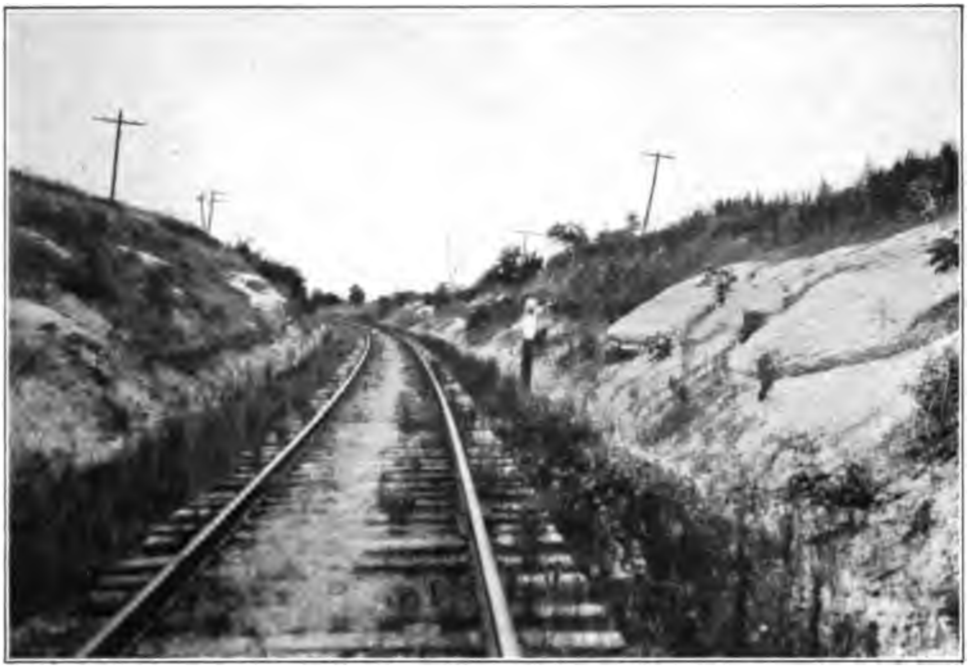
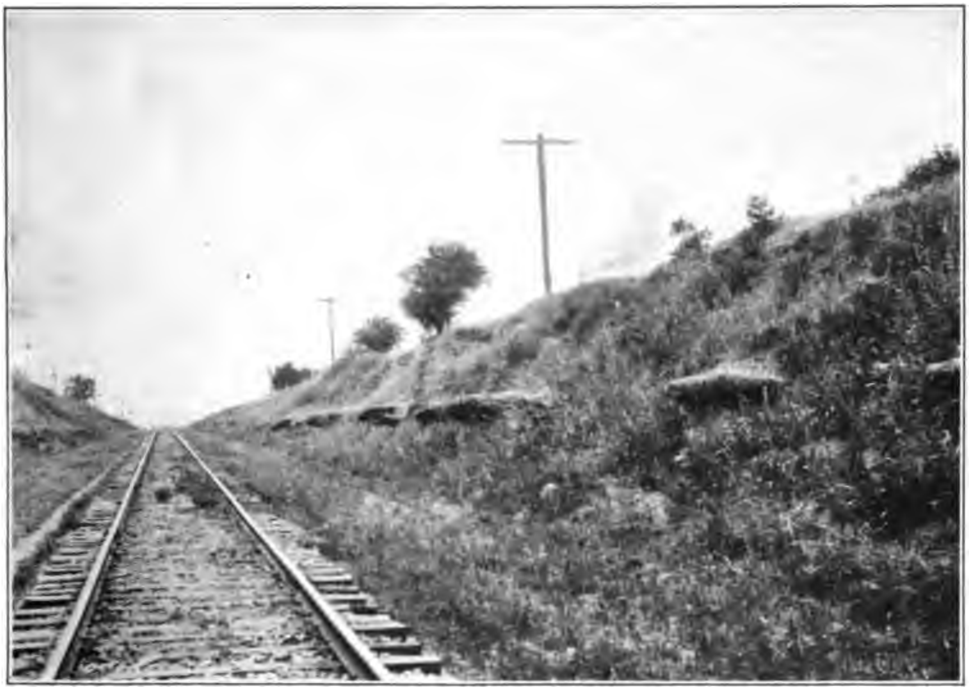
[1] U. S. Geol. Survey Prof. Paper 46, p. 25, 1906.

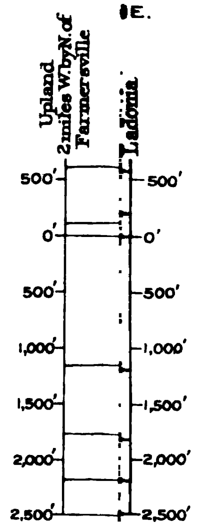
[2] U. S. Geol. Survey Geol. Atlas, Austin folio (No. 76), columnar section 1, 1902.

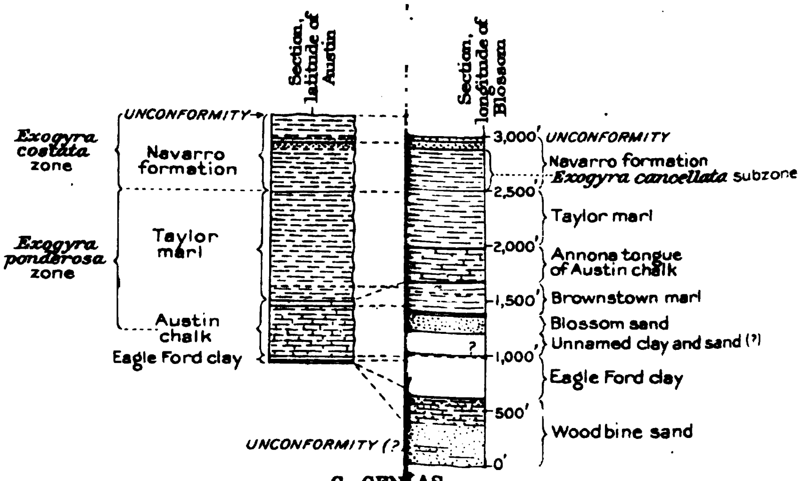


A. BASAL BEDS OF THE PECAN GAP CHALK IN A CUT OF THE GULF, COLORADO & SANTA FE RAILWAY HALF A MILE EAST OF THE STATION AT PECAN GAP, DELTA COUNTY, TEX.



B. FOSSILIFEROUS CONCRETIONARY LAYERS OF CALCAREOUS SANDSTONE IN THE WOLFE CITY SAND IN A CUT OF THE GULF, COLORADO & SANTA FE RAILWAY 1½ MILES EAST BY NORTH OF WOLFE CITY, HUNT COUNTY, TEX.


SW.
E.
Upland 2 miles W. by N. of Farmersville
Ladonia
500'
0'
500'
1,000'
1,500'
2,000'
2,500'


Section, latitude of Austin
Section, longitude of Blossom
UNCONFORMITY
Exogyra costata zone
Navarro formation
Exogyra ponderosa zone
Taylor marl
Austin chalk
Eagle Ford clay
UNCONFORMITY (?)
3,000'
2,500'
2,000'
1,500'
1,000'
500'
0'
UNCONFORMITY
Navarro formation
Exogyra cancellata subzone
Taylor marl
Annona tongue of Austin chalk
Brownstown marl
Blossom sand
Unnamed clay and sand (?)
?
Eagle Ford clay
Woodbine sand

C. GEN AS

the base of the Navarro—that is, with the beds containing *Exogyra cancellata*—that lie above the Pecan Gap chalk member of the Taylor. This age relation is explained by an assumed transgression of the Taylor marl upward in the geologic column from Hunt and Fannin counties, Tex., eastward toward Arkansas.

The clay is overlain by the Wolfe City sand member, described in greater detail below, and this in turn is followed by the Pecan Gap chalk member of the Taylor, also described below, the estimated thickness of which is between 25 and 50 feet.

WOLFE CITY SAND MEMBER.

The Wolfe City sand member of the Taylor marl consists of 75 to 100 feet of fine calcareous gray sand or sandy marl with a few round, oval, or irregular concretions of calcareous sandstone. The sand weathers to greenish yellow. Near the middle of the member is a more or less persistent layer of highly fossiliferous calcareous sandstone of varying thickness, which contains a moderately large but as yet only superficially studied molluscan fauna. (See Pl. XXIX, *B*.) Some beds of calcareous clay occur in the upper part of the member, between the indurated layer and the overlying Pecan Gap chalk member. Several incomplete sections of the sand are described below.

Wolfe City, Hunt County, is situated on the sand, but only small, poor exposures were seen within the town limits. The following section, representing about the middle portion of the member, is afforded by a cut of the Gulf, Colorado & Santa Fe Railway, 1½ miles east by north of Wolfe City. (See Pl. XXIX, B.)

Section in cut of Gulf, Colorado & Santa Fe Railway, 1½ miles east by north of Wolfe City, Tex.

	Feet.
Wolfe City sand member of Taylor marl:	
Poorly exposed yellowish, highly calcareous sand from which weather many small irregular gray sandy concretions of calcium carbonate. Contains *Exogyra ponderosa* Roemer, *Anomia argentaria* Morton, and *Ostrea plumosa* Morton	8
Irregular concretionary layer of yellowish-green fine highly fossiliferous sandstone. See list of fossils below	1-2½
Fine yellowish-green calcareous sand with poorly preserved fossil prints	6

Among the fossils recognized in the indurated layer in the preceding section were the following:

Inoceramus sp.
Pecten sp.
Liopistha (Cymella) bella (Conrad).
Cardium (Criocardium) sp.
Leptosolen biplicatus Conrad.
Corbula crassiplica Gabb.
Cymbophora sp.
Panope sp.
Gastrochaena sp.
Turritella trilira Conrad.
Anchura?
Pugnellus sp.
Morea sp.
Schizobasis sp.
Baculites asper Morton.
Scaphites (two or more species).

The sand and characteristic included concretions are exposed in shallow cuts of the railroad for the next 2 or 3 miles to the east.

Good exposures of the sand occur in ditches paralleling the Gulf, Colorado & Santa Fe Railway four-fifths of a mile to 1 mile east of Pecan Gap, Delta County, where the aggregate thickness revealed is probably 25 or 30 feet. The Pecan Gap chalk is exposed stratigraphically above the sands in a cut about half a mile east of Pecan Gap.

In the public road at Webb Hill, on the northward-facing slope of the South Fork of Sulphur Creek, 4½ or 5 miles southwest of Wolfe City, the indurated layer exposed in the section 1½ miles east by north of Wolf City caps the hill and is underlain by about 30 feet of well-exposed yellowish-green calcareous sand, followed below by 40 or 50 feet of similar material poorly exposed.

Exposures of the Wolfe City sand and the characteristic calcareous concretions were observed in and near the public road 1 to 2 miles south of Kingston, Hunt County, in a public-road ditch, 4½ or 5 miles north by east of Floyd, Hunt County, and in hill slopes south of the Missouri, Kansas & Texas Railway, about 2⅞ miles west of Farmersville, Collin County.

The Wolfe City sand member has thus been definitely traced from a point east of Pecan Gap, in Delta County, to a point southwest of Farmersville, in Collin County, though its boundaries have been only approximately determined.

PECAN GAP CHALK MEMBER.

The uppermost member of the Taylor marl in northeastern Texas consists of about 50 feet of bluish-gray, slightly bituminous, more or less argillaceous and sandy chalk, weathering to light gray and white, to which the name Pecan Gap chalk member is here applied. The chalk contains a moderately large fauna, most species of which are poorly preserved. The lower 10 feet of the chalk is typically exposed in a cut of the Gulf, Colorado & Santa Fe Railway half a mile east of Pecan Gap, Delta County, where the section is as follows:

Section in cut of Gulf, Colorado & Santa Fe Railway, half a mile east of Pecan Gap, Tex.

	Feet.
Pecan Gap chalk member of Taylor marl:	
Blue massive chalk, weathering to light gray and white, becoming sandy, and containing many phosphatic casts of mollusks in the lower 2 or 3 feet (see list below)	10
Wolfe City sand member of Taylor marl:	
Fine yellow argillaceous sand with numerous borings filled with chalky material from above	2
Dark to almost black fine sandy clay, poorly exposed	2

The fossils obtained from the Pecan Gap chalk at this locality are listed below:

Cucullaea sp.
Ostrea plumosa Morton.
Exogyra ponderosa Roemer.
Anomia argentaria Morton.
Crassatellites sp.
Cardium sp.
Gastrochaena sp.
Gyrodes sp.
Anchura sp.
Volutoderma sp.
Actaeon sp.
Nautilus sp.
Baculites asper Morton?
Baculites sp.

Another good exposure of the chalk is in the bed and banks of a small stream on the Cox place, 3 miles east by south of Wolfe City. Here the fresh chalk is bluish gray and slightly bituminous, and weathers light gray and white. The maximum thickness observed at any one place along the branch is 6 feet. Fossils were recognized as follows:

Cucullaea sp.
Inoceramus sp.
Ostrea plumosa Morton.
Gryphaea vesicularis Lamarck, var.
Exogyra ponderosa Roemer.
Lima sp.
Paranomia sp.
Pholadomya sp.
Veniella sp.
Crassatellites sp.
Cardium spillmani Conrad.
Gastrochaena sp.
Xenophora leprosa Morton?
Gyrodes sp.
Anchura sp.
Pyropsis sp.
Volutoderma sp.
Actaeon?
Nautilus sp.
Turrilites?
Baculites asper Morton?
Baculites sp.

A thickness of 5 feet of the chalk was examined in the bed of the south fork of Sulphur Creek near Wilsons Crossing, 4½ or 5 miles due south of Wolfe City, and poor exposures were noted in public roads 1 to 3 miles west of Wilsons Crossing in Hunt County. The chalk outcrops in the vicinity of Whiterock, a village 4 miles northeast of Kingston, Hunt County, where it is overlain by yellowish, somewhat sandy clay marl, and poor exposures of argillaceous chalk were seen in places along the public road for 4 or 5 miles south by west of Whiterock. The chalk also extends at least 2 miles north of Whiterock, where cisterns have been dug into a sandy facies of the member at several farmhouses. The chalk belt is crossed by the Missouri, Kansas & Texas Railway (McKinney branch) at Farmersville, Collin County, small exposures appearing on and near the railway for a mile or more both east and west of the station. The belt is also crossed by the St. Louis & Southwestern Railroad about midway between Nevada and Lavon, Collin County, where an outcrop of the chalk was seen in the bank of a small creek.

The largest collection of fossils yet obtained from the Pecan Gap chalk was made by Mr. and Mrs. D. A. Saunders, of Greenville, Tex., on the Jim Burnett farm, 6 miles northwest of Greenville, 1 mile west of Kellog, Hunt County. This collection was sent to the National Museum for identification and was studied, though not critically, by the writer, who recognized the following forms, many of which were too poorly preserved for specific identification:

Hemiaster aff. H. lacunosus Slocum.
Hemiaster sp.
Serpula (two or more species).

Cucullaea (two or more species).
Pteria sp.
Inoceramus sp.
Ostrea sp.
Gryphaea vesicularis Lamarck, var.
Exogyra ponderosa Roemer.
Exogyra ponderosa var. erraticostata Stephenson.
Exogyra costata Say (a small, nontypical form).
Pecten quinquecostatus Sowerby.
Pecten sp.
Anomia argentaria Morton.
Lima sp.
Trigonia sp.
Pholadomya sp.
Modiolus sp.
Clavagella armata Morton?
Liopistha (Cymella) sp.
Liopistha protexta Conrad?
Cuspidaria aff. C. jerseyensis Weller.
Crassatellites sp.
Radiolites austinensis Roemer.
Tenea sp.
Cardium sp.
Cyprimeria alta Conrad?
Legumen ellipticus Conrad.
Martesia sp.
Pleurotomaria sp.
Gyrodes petrosa (Morton).
Gyrodes sp.
Turritella sp.
Anchura (two species).
Pugnellus sp.
Pyropsis (two species).
Liopeplum sp.
Volutoderma sp.
Actaeon?
Nautilus sp.
Baculites (two or three species).
Turrilites (two species).
Scaphites (three or four species).
Corax falcatus Agassiz (shark teeth).
Lamna sp. (shark teeth).

Gordon[1] recognized the chalk member to which the name Pecan Gap is here applied, but he regarded it as a part of the Navarro formation and correlated it with the "Saratoga" chalk member of the Marlbrook marl of southwestern Arkansas. The Pecan Gap fauna, however, belongs to the upper part of the *Exogyra ponderosa* zone, whereas that of the "Saratoga" is referable to the upper part of the *E. cancellata* subzone of the *Exogyra costata* zone, which is definitely younger and higher. The possibility is recognized that the Pecan Gap chalk may transgress upward in the geologic column from Delta County, Tex., eastward toward Arkansas, being continuous with the "Saratoga" chalk in Arkansas; however, it has not been traced across the interval, although an attempt was made to find it south of Clarksville in Red River County. In view of the adverse evidence afforded by the faunas, therefore, the assumption that the two chalks are identical and continuous is not justified by the present known facts.

NAVARRO FORMATION.

The Navarro formation in northeastern Texas consists of marine calcareous shaly clays, sandy clays, fine gray sands, and argillaceous sands with local indurated portions in the form of calcareous septaria or concretionary sandstone layers. These deposits are estimated to attain a thickness of not less than 800 feet. The formation is probably susceptible of separation into at least three members but has not yet been studied in this area in sufficient detail, either stratigraphically or paleontologically, to admit of mapping the subdivisions, even approximately.

The lower 300 or 400 feet of the formation consists of gray calcareous shaly clay or marl that produces a dark-gray or black soil and carries a distinctive fauna, the most significant species of which are *Exogyra cancellata* Stephenson, found at several localities near Cooper and Greenville, and *Anomia tellinoides* Morton, found at one locality near the Texas & Midland Railroad 2 miles west of Cooper. This is the *Exogyra cancellata* subzone, which forms the basal part of the *E. costata* zone and which has been traced throughout the Atlantic and Gulf Coastal Plain from New Jersey to Kaufman County, Tex., and has been recognized at Ciudad del Maiz, San Luis Potosi, Mexico, about 440 miles south of Eagle Pass, Tex. This subzone is represented in southwestern Arkansas by the upper half or more of the Marlbrook marl with the exception of approximately the upper half of the "Saratoga" chalk member, which forms the upper 20 to 25 feet of the Marlbrook.

The basal clays of the Navarro are overlain by fine gray sands and more or less sandy clays, 100 feet or more in thickness, which have been only superficially studied in northeastern Texas, where they have yielded only a few poorly preserved fossils. These beds correspond approximately to the Nacatoch sand of southwestern Arkansas, which carries a moderately large fauna, and to the sandy beds in the vicinity of Kaufman County and near Chatfield and Corsicana, Navarro County, Tex., which have yielded a large and incompletely described fauna. The sandy beds are therefore to be correlated approximately with the middle portion of the *Exogyra costata* zone of the Atlantic and Gulf Coastal Plain.

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[1] U. S Geol. Survey Water-Supply Paper 276, p. 26, 1911.

Farther south in Texas, from the vicinity of Corsicana, Navarro County,[1] to Mexia and Groesbeck, Limestone County,[2] sand that has been correlated with the Nacatoch sand of Arkansas is overlain by over 500 feet of shaly clay that probably represents the Arkadelphia clay of Arkansas. This higher clay has not been recognized within the area shown on the map accompanying the present report, and there is some evidence that it has been cut out by a northwestward overlap of Eocene strata. The boundary between the Navarro formation and the Eocene has, however, not been traced in detail in this area.

TERTIARY SYSTEM.

EOCENE SERIES.

The southeastern part of the area under consideration, including most of Hopkins County and the southeastern part of Hunt County, is underlain by deposits of sand and clay of Eocene age, belonging in part to the Midway formation and in part to the Wilcox formation, which overlies the Midway. The Midway rests upon the Navarro formation of the Upper Cretaceous, from which it is separated by an erosion unconformity representing a long interval of geologic time. This statement is based not upon observations made in this particular area, where the contact has not been accurately determined and traced, but upon the known fact that throughout the Atlantic and Gulf Coastal Plain the unconformity separating Upper Cretaceous deposits from the overlying Eocene represents a very long time, during which this vast region was above sea level undergoing erosion, prior to the later marine submergence and deposition of Eocene strata.

STRUCTURE.

GENERAL RELATIONS AND ATTITUDE OF THE DEPOSITS.

An examination of a generalized geologic map of the south-central United States would show that the vast stretch of the Coastal Plain bordering the Gulf of Mexico is underlain by a series of sediments of Cretaceous, Tertiary, and Quaternary age, and that north and west of the Coastal Plain in Arkansas, Oklahoma, and central Texas rocks of much greater age, formed during Paleozoic and pre-Paleozoic time, appear at the surface. In reality the ancient rocks underlie the entire Gulf region, forming a supporting basement for the younger rocks, which overlap and conceal them as far northward and westward as would be indicated on the generalized geologic map. Along this boundary the upper peneplaned surface of the ancient basement rocks dips beneath the younger deposits, becoming deeper gulfward until along the coast it probably lies too deep to be reached by modern well-drilling methods.

In the area in northeastern Texas now under consideration the basement rocks do not appear at the surface, but they outcrop farther north, 10 to 30 miles north of Red River, in the southeastern part of Oklahoma, and farther west, in Montague and Wise counties, Tex. In the northwestern part of the area shown on the geologic map (Pl. XVII) the basement rocks lie in places within 350 feet of the surface, and in the southeast corner of the area, where their depth is greatest, they are estimated to lie between 4,000 and 5,000 feet below the surface.

The dip of the upper surface of the basement rocks ranges from 40 feet or less to the mile in the western part of the area to 70 feet or more to the mile in places in the east-central part. At Bowie, Montague County, Tex., near the western edge of the outcrop of Cretaceous rocks, the altitude of the surface of the basement rocks is approximately 1,100 feet above sea level; at Farmersville, Collin County, 90 miles east by south of Bowie, the basement is estimated to lie about 2,800 feet below sea level, making a general dip of 43 feet to the mile in the intervening area. Near Boggy

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[1] Matson, G. C., and Hopkins, O. B., The Corsicana oil and gas field, Tex.: U. S. Geol. Survey Bull. 661, pp. 218-221, pls. 19 and 20, 1917.

[2] Matson, G. C., Gas prospects south and southeast of Dallas: U. S. Geol. Survey Bull. 629, pp. 21, 22, pl. 7, 1916.

Depot, in Atoka County, Okla., the contact between the basement rocks and the overlying Cretaceous strata is about 550 feet above sea level; near Wolfe City, Hunt County, Tex., 64 miles south by east of Boggy Depot, the basement rocks are estimated to be 2,800 feet below sea level, indicating a general dip of 52+ feet to the mile. Locally, however, the dip of the basement surface is probably much greater than 52 feet and may reach several hundred feet to the mile. These figures are based partly on assumed thicknesses, particularly of the formations composing the Comanche series, and are subject to correction when the facts are known.

The geologic map (Pl. XVII) shows that the strike of the beds composing the Cretaceous formations of northeastern Texas is approximately east in the eastern parts of Lamar and Delta counties; it swings around toward the south, farther west and southwest, in Fannin and Hunt counties; and becomes south by a few degrees west in the southern parts of Hunt and Collin counties. The dip is gulfward at right angles to the strike except locally, where the normal attitude of the beds has been disturbed by earth movements. The general dip is probably somewhat less than the inclination of the surface of the basement rocks on which the Cretaceous beds rest. The general range of dip is believed to be from 30 feet or less to the mile to 80 feet or more to the mile, but there is evidence that locally, as along the southern limb of the Preston anticline near Pottsboro, the beds may dip as much as 300 feet to the mile.

The uniform monoclinal attitude which so generally characterizes the Cretaceous formations of the Gulf Coastal Plain is interrupted in this area by at least two pronounced deformations, the Preston anticline and the Leonard-Celeste monoclinal nose, which are described below. Other similar deformations, though probably much smaller, may be discovered as a result of future more detailed investigations.

Faulting of small magnitude occurred in places in the area, probably as a result of the movements which produced the folds; positive evidence of small faults was obtained at several localities. The building-stone facies of the Annona tongue of the Austin chalk exposed in the quarries and small branch streams at and within a few hundred yards southeast of Gober, in the southern part of Fannin County, is considerably disturbed by faults of small displacement; one fault running approximately northeast exhibits a displacement of 15 feet. At the crossing of a public road over Choctaw Creek 3½ miles north by east of Luella, Grayson County, a fault trending N. 55° E. exhibits a displacement of 8 inches. Messrs. Hopkins and Powers indicate on their structure map a fault of relatively small displacement southeast of Bonham, Fannin County, which involves the basal strata of the Annona tongue and the clay that immediately underlies the chalk. (See Pl. XVII.)

PRESTON ANTICLINE.

The Preston anticline is a plunging upfold of Cretaceous strata that is most conspicuous in the southern parts of Marshall and Bryan counties, Okla., and the northern part of Grayson County, Tex., but is measurably manifested in the direction of its southeastward-trending axis as far as the vicinity of Gober in Fannin County, Tex. The approximate position of the axis of the anticline is indicated on Plate XVII by a dashed line.

Where the anticline is best developed in the Red River valley, northwest of Denison, the Comanche series of formations, which would normally be buried beneath the overlapping younger strata of the Gulf series, have been warped upward approximately 800 feet, and the beds of the overlying Gulf series have thus been subjected to erosion, which has entirely removed not only the Gulf series but also much of the underlying Comanche series from a considerable area along the axis of the uplift. Here the outcrops of the formations of the Comanche series parallel the sides of the anticline and wrap about its southeastward-plunging nose in typical fashion; the strike of the formations of the area, which would normally range from west to southwest, is distinctly bowed to the southeast where the formations cross the axis of the anticline, and this deflection of the strike is manifested at least as far to the southeast as Gober, Fannin County.

From the vicinity of Preston Bend in northern Grayson County, where the maximum uplift of the Cretaceous strata above the position they would have occupied had there been no folding is approximately 800 feet, the amount of deformation gradually decreases to the southeast along the axis of the fold, and near Gober, Fannin County, the uplift is very slight.

Section A in Plate XXX is drawn approximately at right angles to the axis of the anticline from a point near the northeast corner of the Denison quadrangle, in Bryan County, Okla., southwest to a point 3¼ miles north of Fink, Grayson County, Tex., thence south to a point 1 mile north by west of Pottsboro, thence south-southeast to Sherman. The surface profile is based on the data recorded on the Denison topographic map, and the structure lines are based partly on outcrops and partly on data afforded by wells. This section is believed to be approximately accurate where it crosses the main part of the anticline north of Pottsboro, the position of the lines there having been checked against the structure contours established by Messrs. Hopkins and Powers. (See Pl. XVII.)

The structure contours shown on Plate XVII are generalized from larger-scale maps prepared by Messrs. Hopkins, Powers, and Robinson, as elsewhere explained. Their method was to determine the altitude of key rocks at as many points as possible, by means of aneroid readings corrected for changes of atmospheric pressure by barograph records obtained simultaneously at the bases from which the field work was done, and to supplement these surface observations with data afforded by all available well records.

The contours on the main part of the Preston anticline in the northern part of Grayson County, Tex., and the southern parts of Marshall and Bryan counties, Okla., show the altitude above sea level of the top of the Goodland limestone. The extension of the anticline into Fannin County is indicated by the southeastward deflection of the contours showing the altitude of the base of the Ector tongue of the Austin chalk in the vicinity of Ector, by a less pronounced deflection of the contours showing the base of the Annona tongue of the Austin chalk between Dodd City and Randolph, and by only a faint bending of the contours showing the top of the Annona tongue northeast of Gober. The last-mentioned place is approximately at the point where the anticline dies out toward the southeast. A shallow syncline parallels the anticline along its northeast side in Fannin County, as indicated by a deflection to the northwest of the several sets of contours. A structural terrace on and slightly south of the plunging nose of the anticline is indicated by the spacing of the contours 2 to 6 miles northeast of Pottsboro, Grayson County.

The dip of the strata of the Comanche series away from the axis of the Preston anticline ranges from a few feet to a little more than 300 feet to the mile. In general, the south limb is a little steeper than the north limb. The steepest part of the anticline is on the south limb in a northwest-southeast stretch about 3 miles long northeast of Pottsboro (see Pl. XVII), where, as indicated by the contours, the maximum dip of slightly more than 300 feet to the mile is attained by the Goodland limestone. This relatively strong dip is also clearly manifested in outcrops of the Main Street limestone, the next to the highest member of the Denison formation, whose strata in conjunction with the "Quarry" limestone form a low strike ridge beginning about 2 miles east of Pottsboro and extending in a northwesterly direction for about 2 miles. Along this ridge the Main Street limestone, though poorly exposed, obviously dips strongly to the southwest, in places as much as 20° or even more. The pronounced narrowing in the belt of outcrop of the Woodbine formation resulting from the unusually steep inclination of the strata in this belt was perhaps the chief basis for the postulation of the so-called Cook Spring fault by Taff[1] and Leverett and by Hill.[2]

The nature of the earth movements that produced the Preston anticline is imperfectly known, though the assumption is warranted that the movements had their origin in the basement rocks that underlie the overlapping Cretaceous sediments. As the axis of the anticline trends approximately parallel to most of the major faults and folds in the Arbuckle Mountains in Oklahoma, the assumption also seems warranted that this uplift is directly related to the Arbuckle uplift, and that the folding of the Cretaceous strata was merely incidental to the upbowing of these older basement rocks.

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[1] Texas Geol. Survey, Fourth Ann. Rept. for 1892, pp. 297, 298, 1893.

[2] U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, pp. 384, 385, pl. 66, 1901.

LEONARD-CELESTE MONOCLINAL NOSE.

The structure contours showing the altitude above sea level of the top of the Annona tongue in the vicinity of Leonard in southwestern Fannin County, Tex., are deflected rather sharply to the south. (See Pl. XVII.) This deflection is also clearly manifested in the outcrop of the Annona, the strike of whose uppermost beds in the vicinity of Leonard shows a distinct bulge to the south. A similar and even stronger southward or southeastward deflection is exhibited by the belts of outcrop of the Wolfe City sand and Pecan Gap chalk members of the Taylor marl between Celeste and Greenville, in Hunt County. (See Pl. XVII.) These are the surface manifestations of a fold in the underlying Cretaceous strata of the kind described by F. G. Clapp[1] as a monoclinal nose. For convenience this fold is called the Leonard-Celeste monoclinal nose. The areal distribution of the formations of the Gulf series in Fannin, Collin, and Hunt counties strongly suggests that this fold is the deflected southward extension of the Preston anticline, and this was the interpretation at first placed upon the structure. However, the structure contours on the base of the Annona tongue established by Messrs. Hopkins and Powers (see Pl. XVII) indicate that this relationship is only apparent, the Leonard-Celeste fold being separate from the Preston anticline, though doubtless closely related to it both physically and in manner and time of origin. The axis of the fold appears to trend south by east through Leonard and a mile or so west of Celeste and Kingston, Tex.

The surface evidence of the existence of this fold appears to be corroborated by the records of two wells nearly in line with the general strike of the formations—one near Wolfe City, where the top of the Annona tongue of the Austin chalk was struck at a depth of about 510 feet (160 feet above sea level), and the other at Celeste, where the Annona was reached at a depth of only 300 feet (360 feet above sea level). Section B, in Plate XXX, drawn approximately at right angles to the axis of the fold, from Ladonia, Fannin County, west by south to a point 1¾ miles northeast of Wolfe City, in Fannin County, thence southwest by way of Celeste to a point 2 miles west by north of Farmersville, Collin County, shows this upbowing of the strata in the vicinity of Celeste. The surface profile in this section is based in part on railroad elevations and in part on aneroid barometer readings, and the structure lines are based on surface outcrops and on data afforded by the wells at Celeste and Wolfe City previously mentioned and by one well at Ladonia. The depth to the Woodbine in these three wells, if their logs are properly interpreted, apparently confirms the evidence afforded by the chalk. At the southwest end of the section near Farmersville the Annona, as estimated from surface outcrops and assumed thicknesses, has again sunk back to a level approximately the same as near Wolfe City, or a little deeper.

OIL AND GAS PROSPECTS.

Oil and gas have frequently been found in the upbowed or anticlinal portions of strata that have been subjected to warping or folding by earth forces, and although these substances are not confined exclusively to such structural features, no argument is needed to convince the practical operator that his best chance of success in untested territory lies where folded strata are known to exist. The Preston anticline and the Leonard-Celeste monoclinal nose, described above, will therefore not fail to attract the attention of persons interested in the discovery of reservoirs of oil and gas.

In this paper only the more obvious conclusions in regard to the occurrence of oil and gas, which might be readily deduced by any oil geologist or practical oil operator from the facts already presented, will be briefly discussed. A more detailed discussion of the structural features of this area and an adjoining area on the northwest in Oklahoma, with particular reference to the occurrence of oil and gas in both the Cretaceous and underlying basement rocks, will be given by Messrs. Hopkins, Powers, and Robinson in an economic paper to be published later.

The most conspicuous part of the Preston anticline, in Grayson County, Tex., and Marshall and Bryan counties, Okla., has already been recognized by oil prospectors, and test wells have been drilled on different parts of the uplift. Gas reported to come from the lower part of the Trinity sand at depths of less than 700 feet has already been discovered near the axis of the anticline in the southern part of Marshall County, where at least a dozen test wells have been drilled. Of these wells six, located in a group in the southeast corner of T. 6 S., R. 5 E., and the northeast corner of T. 7 S., R. 5 E., are classed as producing gas wells, and each of three of them is reported to yield from 1,500,000 to 2,500,000 cubic feet of gas daily. This pool is known as the Enos gas field. In June, 1918, an oil well near the crest of the anticline in sec. 23, T. 7 S., R. 5 E., was completed in the Trinity sand at a depth of 260 feet and was reported to produce 20 barrels of oil daily. Showings of oil or gas, or both, have been reported from the Trinity sand in some of the other wells penetrating the strata involved in the anticline. The Madill oil field,[1] farther north in Marshall County, in the southeast corner of T. 5 S., R. 5 E., which yields small commercial quantities of an exceptionally light grade oil from the Trinity sand,[2] is not connected with the Preston anticline but with another distinct though approximately parallel fold, as shown by an unpublished structure contour map prepared by Messrs. Hopkins, Powers, and Robinson.

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[1] Geol. Soc. America Bull., vol. 28, p. 572, fig. 8, 1917.

Of the geologic subdivisions involved in the Preston anticline and its extension to the southeast in Fannin County, four are composed in part of sandy strata, which exhibit a sufficient degree of porosity, at least in their outcropping portions, to fit them to serve as reservoirs for the storage of oil or gas. They are, in ascending order, the Trinity sand, the Pawpaw sandy member of the Denison formation, the Woodbine sand, and sandy beds in the upper part of the Eagle Ford clay.

The occurrence of gas and some oil in the Trinity sand along the axis of the fold in the southern part of Marshall County, Okla., has already been demonstrated. The amount of gas and the volatile products of oil that may once have been contained in the sand and have since escaped where the formation is exposed in the crest of the fold can, of course, only be conjectured. The Trinity dips below the surface on the plunging nose of the anticline in the Red River valley, about 5½ miles north by west of Denison.

A traveler passing to the southeast along the axis of the anticline would cross successively the outcropping strata of the sandy formations mentioned above, with intervening bands of nonsandy clay and chalk, each in turn dipping below the surface down the nose of the anticline. After crossing the limestones and clays of the Comanche series above the Trinity he would come first to the narrow belt of sand of the Pawpaw sandy member of the Denison formation near the northeast corner of Grayson County, the wider sandy belt of the Woodbine in the northwest corner of Fannin County, and the narrow strip of sand forming the uppermost part of the Eagle Ford formation at Ector, in Fannin County.

A well on the axis of the anticline near the northwestern part of Fannin County would start in the Woodbine sand, below which it would encounter two of the possible oil or gas bearing sands, the Pawpaw and the Trinity. The top of the Pawpaw would probably be reached at depths of 50 to 500 feet and the top of the Trinity at depths of 500 to 1,000 feet, the depth depending on the exact location of the well.

A well at Ector would start in the sand at the top of the Eagle Ford and would penetrate the Woodbine sand at an estimated depth of 400 to 900 feet, the sandy beds of the Pawpaw at an estimated depth of 925 to 975 feet, and the Trinity sand at an estimated depth of 1,300 to 1,800 feet.

A well starting at the top of the Annona chalk northeast of Gober would penetrate the sandy beds at the top of the Eagle Ford at an estimated depth of 800 to 900 feet, the Woodbine sand at an estimated depth of 1,300 to 1,850 feet, the sandy beds of the Pawpaw at an estimated depth of 1,900 to 1,950 feet, and the Trinity sand at an estimated depth of 2,300 to 2,800 feet.

So far as known to the writer no wells have been drilled that would serve as an adequate test of the occurrence of oil or gas in the Leonard-Celeste monoclinal fold. The deepest well concerning which information has been obtained is the 1,554-foot water well at Celeste, perhaps a mile or a mile and a half east of the axis of the fold. This well is believed to have reached the uppermost sandy stratum of the

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[1] Taff, J. A., and Reed, W. J., The Madill oil pool, Okla.: U. S. Geol. Survey Bull. 381, pp. 504-513, 1910.

[2] Oklahoma Geol. Survey Bull. 19, pt. 2, pp. 316-320, 1917.

Woodbine formation at a depth of 1,535 feet. The sandy beds at the top of the Eagle Ford were not recognized in the well and may here be represented by nonsandy clay. The sandy beds of the Pawpaw would be reached here at an estimated depth of 2,200 feet, and the top of the Trinity sand at an estimated depth of 2,600 feet.

At Greenville, which is probably near the axis of this fold, all the possible oil sands of the Cretaceous, except the Nacatoch, would be penetrated by a well probably less than 3,500 feet deep. These would include, in descending order, the Wolfe City sand member of the Taylor marl, the sandy member at the top of the Eagle Ford, which would probably be very thin and might be represented entirely by clay; the sands of the Woodbine formation; the Pawpaw sandy member of the Denison; and, finally, the Trinity sand.

In pointing out the existence of the folds described above the writer does not wish to be understood as urging the probability of the occurrence of oil and gas in association with the folds, though he feels that the facts warrant an optimistic attitude on the subject.

Four factors are generally regarded as essential to the occurrence of oil and gas—an adequate source of hydrocarbons, such as petroliferous shales or clays; porous beds intimately connected with the source to serve as reservoirs; suitable structure for the concentration of the oil and gas; and suitable hydrostatic conditions. Two of these factors appear to be favorable in this area; porous formations for the retention of the oil are present, and structural folds exist similar to those in which oil and gas are known to have accumulated elsewhere. The factor of source, although less completely known, also appears to be favorable, for the chalks and some of the clays that intervene between the sandy formations are distinctly bituminous. In regard to the fourth factor, there is no known reason why the ground-water conditions in the Cretaceous beds of this area should be essentially different from those of the other oil and gas fields of the Gulf Coastal Plain.

SUMMARY.

1. *Areal geology.*—Important revisions in the areal distribution of the formations of both the Comanche and Gulf series, as previously mapped in this area, are indicated in Plate XVII, and three new mappable units are recognized, including the Ector tongue of the Austin chalk and the Wolfe City sand member and Pecan Gap chalk member of the Taylor marl.

2. *Stratigraphy.*—A new interpretation of the stratigraphic and age relations of the formations of the Gulf series based on the following facts is presented (see Pl. XXX, *C*): (*a*) The recognition of the so-called "fish-bed conglomerate" of Taff (see p. 149) as the probable base of the cycle of sedimentation which has its typical expression in the Austin chalk; (*b*) The recognition of a relatively thin tongue of chalk, the Ector tongue, extending northeastward from the base of the main body of the Austin chalk in the vicinity of Ector, Fannin County; (*c*) the eastward merging of approximately the basal half of the Austin chalk, with the exception of the Ector tongue, into equivalent nonchalky clay in Fannin County: (*d*) the correlation of the Blossom sand with the upper part of the typical Austin chalk of Travis County, Tex., instead of with the upper part of the Eagle Ford formation, as previously correlated (see pp. 152-153 and Pl. XXX, *C*); (*e*) the upward transgression in the geologic column of the upper part of the Austin chalk from Travis County northward; (*f*) the recognition of the Annona ("White Cliffs") chalk of Hill as a large tongue connected with the main body of the Austin chalk; (*g*) the discrimination of the Wolfe City sand and Pecan Gap chalk as upper mappable members of the Taylor marl.

3. *Structure.*—The structural feature in the northern part of Grayson County, Tex., and the southern parts of Marshall and Bryan counties, Okla., heretofore regarded as an uplifted fault block which brought the formations of the Comanche series to the surface, where normally they would lie deeply buried, is shown to be instead an anticlinal uplift, the Preston anticline, with which, so far as known, no major faults are directly associated. A newly recognized structural feature, called the Leonard-Celeste monoclinal fold, in southwestern Fannin and northwestern Hunt counties, is described. Structure contours have been established by Messrs. Hopkins, Powers, and Robinson, showing the altitude above sea level of the top of the Goodland limestone about the flanks of the Preston anticline, and Messrs. Hopkins and Powers have established contours showing the altitude of the base of the Ector tongue and the base and top of the Annona tongue of the Austin chalk in certain areas in Fannin, Grayson, and Hunt counties. (See Pl. XVII.)

4. *Oil and gas.*—A brief statement of the factors controlling the occurrence of oil and gas with particular reference to this area is given, and the hope is expressed that future prospecting may result in the discovery of these substances in commercial quantities somewhere in association with the Preston anticline or with the Leonard-Celeste monoclinal fold.

SOME AMERICAN CRETACEOUS FISH SCALES, WITH NOTES ON THE CLASSIFICATION AND DISTRIBUTION OF CRETACEOUS FISHES.

By T. D. A. Cockerell.

PREFACE.

By T. W. Stanton.

Fish remains are extremely abundant in several Cretaceous formations of the Rocky Mountains and Great Plains, but except in the Niobrara formation of Kansas, a fish skeleton well enough preserved for description or identification is the greatest rarity. The fishes are represented by separate scales, in some places associated with a few vertebrae and other fragmentary bones or by isolated teeth. In the original descriptions of both the Mowry and the Aspen shales of Wyoming the presence of fish scales is mentioned as a characteristic feature. Fossils of other classes are usually very rare in beds containing many fish scales. Many of the scales are beautifully preserved and show varied forms and more or less complex sculpture.

It had long been regretted that these fish scales had not been studied systematically, and when several papers on the scales of living and fossil fishes were published by Prof. Theodore D. A. Cockerell,[1] of the University of Colorado, Boulder, Colo., the hope was again quickened that these Cretaceous fish scales might prove to be of some value in stratigraphic identifications and correlation. Prof. Cockerell's offer to study fish scales collected by the United States Geological Survey was therefore welcomed, and early in 1916 the material from the Western States was placed in his hands. As a result of its study the accompanying paper has been prepared.

In connection with the Survey's stratigraphic and areal work on the coal and oil fields of the Rocky Mountain region many small lots of fish scales have been obtained from the Mowry shale, from the Aspen shale, and from other beds of about the same age in the areas where these shales are not characteristically developed, but no attempt has been made to do thorough collecting even in these formations, because no one in the Survey was qualified to identify the scales. The scales from other formations in the same region have been obtained incidentally in collecting invertebrate fossils and are so few in number that they probably do not fairly represent the fish faunas of the seas in which the formations were deposited. Similarly, the four species based on scales from the Chico group were all obtained in the Moreno formation at two neighboring localities on the west side of San Joaquin Valley, Cal., and can only be regarded as suggestive of the relationship, or lack of relationship, between the Cretaceous fish faunas of the Pacific coast and those of the Rocky Mountain region. The enormously thick section referred to the Chico group in this part of California has been divided by Anderson and Pack [2] into the Panoche formation below and the Moreno formation at the top. The Panoche formation is said to have a maximum thickness of 21,000 feet and the Moreno formation 2,500 or 3,000 feet. Fish scales are known to be present in the Cretaceous formations of the Coastal Plain, extending from New Jersey to Texas, but no attempt has yet been made to assemble them for study. The collections here treated are all of Upper Cretaceous age—that is, they are younger than the Comanche and Shasta series.

A brief statement will show the relative stratigraphic positions from which the fish scales described have been obtained and will explain why beds of approximately the same age are referred to different formations in different areas. The standard marine Upper Cretaceous section of the Upper Missouri region is as follows:

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[1] The scales of fresh-water fishes: Biol. Bull., vol. 20, pp. 367-386, 1911. Observations on fish scales: U. S. Bur. Fisheries Bull., vol. 32, pp. 119-174, 1912. Some fossil fish scales: Zool. Anzeiger, Band 45, pp. 189-192, 1914. Scales of Panama fishes: Washington Biol. Soc. Proc., vol. 28, pp. 151-159, 1915.

[2] U. S. Geol. Survey Bull. 603, pp. 34-57, 1915.

Montana group:
  Fox Hills sandstone.
  Pierre shale.
Colorado group:
  Niobrara limestone.
  Benton shale.
Dakota sandstone.

In Colorado east of the Rocky Mountains and over a considerable part of the Great Plains a limestone (Greenhorn limestone) is developed in the midst of the Benton shale, so that the Benton shale interval consists of three formations—the Carlile shale, Greenhorn limestone, and Graneros shale. In parts of the same area the Niobrara is also separable into two formations—the Apishapa shale above and the Timpas limestone below.

In the eastern half of Wyoming and around the Black Hills the Mowry shale is conspicuous in the lower part of the Colorado group as a hard, platy, ridge-forming shale, full of fish scales. In the Black Hills, where the Greenhorn limestone is recognized and the Benton is therefore divisible into three formations, the Mowry shale is treated as a member of the Graneros shale. In some areas where the Benton is not divided the Mowry is called a member of the Benton; in the Big Horn Basin it is recognized as an independent formation lying between the Frontier formation above and the Thermopolis shale below.

The Aspen shale, which certainly includes rocks of the same age as the Mowry shale, is restricted to western Wyoming, which is also the typical area of the Frontier formation. The section there is as follows:

Adaville formation.
Hilliard shale.
Frontier formation.
Aspen shale.
Bear River formation (restricted to western Wyoming).

In this section the time equivalent of the Colorado group extends from the top of the Bear River formation to about the middle of the Hilliard shale, and the upper part of the Montana group is probably absent. In western Colorado the whole of the Colorado group and the lower part of the Montana group are represented by an undivided mass of shale called the Mancos shale, and this is overlain by the coal-bearing Mesaverde formation, followed by the Lewis shale and in the southwest by the Pictured Cliffs sandstone. The Mesaverde formation is also recognized over a large part of Wyoming, and the only fish scales found in it were obtained in marine and brackish-water beds of the Rock Springs field.

Another set of names has been used in northern Montana on account of the development of different stratigraphic units. There the great shale mass corresponding to the Mancos extends only to the top of the Colorado group and is therefore called the Colorado shale. Above it in order come the Eagle sandstone, the Claggett shale, the Judith River formation, and the Bearpaw shale. Locally this succession is modified by the merging of the Claggett with the Eagle and Judith River and the development of the Horsethief sandstone above the Bearpaw shale.

The approximate relations of the above-mentioned local subdivisions of the Colorado and Montana groups are shown in the following table:

Relations of local subdivisions of Colorado and Montana groups.

	Standard section, upper Missouri region.	Eastern Colorado.	Black Hills and eastern Wyoming.	Southern Wyoming.	East side of Big Horn Basin.	Western Wyoming.	Western Colorado.	Northern Montana.
Montana group.	Fox Hills sandstone.	Fox Hills sandstone.	Fox Hills sandstone.					
	Pierre shale.	Pierre shale.	Pierre shale.	Lewis shale.	Meeteetse formation (fresh water).		Pictured Cliffs sandstone (southwestern Colorado).	Bearpaw shale.
							Lewis shale.	
				Mesaverde formation.	Mesaverde formation.	(?) Adaville formation.	Mesaverde formation.	Judith River formation.
				Steele shale.				Claggett shale.
								Eagle sandstone.
Colorado group.	Niobrara limestone.	Apishapa shale.	Niobrara formation.	Niobrara shale.	Cody shale.	Hilliard shale.	Mancos shale.	Colorado shale.
		Timpas limestone.						
	Benton shale.	Carlile shale.	Carlile shale.	Carlile shale.				
		Greenhorn limestone.	Greenhorn limestone.	Frontier formation.	Frontier formation.	Frontier formation.		
		Graneros shale.	Graneros shale. Mowry shale member.	Mowry shale.	Mowry shale.	Aspen shale.		
				Thermopolis shale.	Thermopolis shale.			

INTRODUCTION.

In offering a treatment of Cretaceous fishes, based principally on isolated or detached scales, one runs counter to the practice and prejudice of ichthyologists. The old scale classification of Agassiz has long been discarded and his terms are now used only in a descriptive sense. Even in that sense they are rather unsatisfactory, for there are many entirely different types of cycloid, ctenoid, and ganoid scales. Recent studies of the scales of living fishes show that they present excellent diagnostic characters and are highly distinctive of genera and families, though not always of species. Very closely allied species may have scales which can not be distinguished, the scale characters being more persistent than some of the other more adaptive features on which the species are separated. Some scales, as might be expected, exhibit convergent or parallel evolution, showing similar features in quite different groups of fishes. Facts of this sort are likely to be misleading, but they are in no sense peculiar to lepidology.

In former years a few authors have undertaken to diagnose or recognize Cretaceous fishes from the scales alone. Dr. A. S. Woodward, influenced no doubt by the evident confusion in the application of the names, has set aside these determinations as practically valueless. It was not possible to give a really intelligible account of the fossil teleost scales until those of living fishes had been rather fully investigated. To-day the situation is different, and we feel justified in proceeding on a new basis. The situation is not unlike that found in paleobotany. Students of living plants do not describe species from leaves alone except in the rarest instances. Yet, if paleobotanists had refused to take note of or describe all plant remains that did not include the reproductive parts, our knowledge of the past history of vegetation would to-day be fragmentary indeed. It is true that many of the generic references of fossil leaves are provisional and uncertain, and it is very easy to criticize any paleobotanic work on this basis; yet no careful student of the subject can deny that on the whole the study of fossil leaves has been of immense value for the advancement of botanic science as well as for stratigraphy. After spending much time in the study of fossil plants as well as fish scales, I can affirm that the scales are certainly not less characteristic than the leaves; in fact, the comparison is decidedly in favor of the scales. It can also be said that the scales are at least as distinctive as the fragments of jaws, teeth, and fins that form the basis of so many descriptions of Cretaceous fishes. It is not, however, a question of scales versus bones, where both are available. Throughout the greater part of the American Cretaceous strata distinctive skeletal remains of fishes are extremely scarce; only in the Niobrara can they be said to be at all abundant. On the other hand, scales are plentiful and widespread and may be found in innumerable places where no other fossils are obtainable. Consequently, to refrain from studying these scales is to set aside a valuable aid to stratigraphy as well as a chance of learning in considerable detail what the teleost fauna of the Cretaceous really was. The Cretaceous was a time of extraordinary importance for ichthyology, because it saw the rise and development of the higher fishes, with numerous types clearly pointing toward the modern fauna. For this reason it is especially desirable to note every fact which will throw light upon the Cretaceous history.

The study of fossil scales involves one difficulty. In studying modern fishes the investigator takes the scales from the middle of the side of the fish, where all their characters are fully developed. Scales from other situations may be quite uncharacteristic. Naturally no such selection has taken place in the preservation of the fossils, and consequently the specimens must be regarded with caution and set aside if there is any reason to think that they are not typical. Scales from the region of the caudal peduncle will be comparatively narrow, but their sculpture and markings will be normal. Latinucleate (regenerated) scales are as common among fossils as in recent fishes, and should not be used as types. They can be distinguished by the confused sculpture of the central region, without the fine circuli around the nucleus. In describing scales the free end is spoken of as the apex, the attached end as the base. The teleost scale is made up of fine fibrillae, which are in some genera longitudinal, as in *Amia* and *Albula*, but more usually concentric. In the true clupeids (herrings) they are transverse. These fibrillae are termed the circuli and are not growth lines. Growth lines have often been observed cutting the circuli. In migratory fishes, such as the salmon, the growth lines differ in character and density, according to the environment, and consequently it may be possible to detect evidence of migratory habits in fossil fishes. Lines or grooves radiating from the center of the scale or from its direction are called radii. This term was long ago used by Cope in describing fossil fish scales; and it must be said of Cope that his descriptions of these structures were much better than those of most other authors, though lacking in many desirable details.

As in the case of fossil leaves, descriptions of scales without figures are unsatisfactory, especially if they are to be largely used by stratigraphers who have no intimate knowledge of lepidology. Consequently it has been considered necessary to illustrate this paper fully; and the enlarged figures, from photographs, bear testimony alike to the excellent preservation of much of the material and the skill of the photographer, Mr. W. O. Hazard, of the United States Geological Survey. Only those species have been described and figured which it seemed could be clearly recognized. Various others, evidently distinct but represented by poor or uncharacteristic material, have been set aside for the present. Additional collections, now that attention is called to the subject, will undoubtedly greatly increase the number of known species.

I am particularly indebted to Mr. T. W. Stanton, of the Survey, for assistance of every kind throughout this investigation. Without his kind help I should have found it very difficult to proceed. I am also greatly indebted to my colleague, Prof. J. Henderson, of the University of Colorado Museum, for advice and assistance. Dr. D. S. Jordan has given me much kind advice, though, of course, he is in no way responsible for my manner of treating the subject. He has furnished a manuscript list of all the families and higher groups of fishes, representing his most mature opinions. This I have mainly followed in the present paper. Dr. A. S. Woodward, of the British Museum, has sent me admirable photographs of fossil fish scales, two of which I have reproduced (Pl. XXXVII, figs. 1, 2), and when I was in London he kindly gave me access to the collections of the Museum. Unfortunately at that time I did not know that I should be specially interested in Cretaceous fishes and did not pay particular attention to their scales, except in the case of a few genera. The authorities of the United States National Museum and the American Museum of Natural History very kindly allowed me to examine their materials. I am indebted to the University of Kansas for the photographs of *Hypsodon* (*Portheus*), reproduced in Plate XXXIII, figures 1 and 2.

As students of fossil scales will need specimens of recent species, it may be worth while to explain a simple manner of preparing them. Remove a few scales from the middle of the side of the fish, avoiding regenerated scales, and place them, while wet, upon a slide. The skin covering the exposed part should be removed if it is thick. Cover the scales with a cover glass or, if they are large, with another slide. Hold down with one or more of the metal clamps used in microscopic work. Stick a gummed slide label on each side of the cover glass, overlapping, or, if two slides are used, round the ends of the slides. Remove the clamps when the material is dry, and the scales will remain in place.

STRATIGRAPHIC DISTRIBUTION.

GENERAL FEATURES.

In this discussion we are dealing almost entirely with a marine fauna. Scanty remains from the Judith River beds (see Acipenseridae) are of fresh-water origin, but they do not include any teleost scales. It is not until we come to the base of the Eocene, in the Rocky Mountain region, that we find scales of fresh-water bony fishes,[1] and the species obtained present all the characters of the highly organized modern group Centrarchidae (Micropteridae). The perchlike fishes are not found in American Cretaceous strata, and it is a question whether they may not have evolved in fresh water and later taken to the sea. At any rate, it must be said that so far as we know at present the Tertiary fishes mark a considerable advance on or at least change from their Cretaceous predecessors. It ought to be possible as a rule to distinguish a Cretaceous from a Tertiary deposit by means of a single well-preserved fish scale. The exceptions will be found in those groups which range with little change from the Cretaceous to the present day—the berycoids, clupeids, or hemiramphids. In such groups only the recognition of the species and its identification with one from beds of known age could be of any service. Such a scale as that of *Pomolobus? chicoensis*, from the Chico, might belong anywhere from that time to the present day. So, also, with *Hemilampronites hesperius*, from the Fox Hills.

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[1] A possible exception is U. S. Geological Survey locality 6603, in the Uinta Basin, Utah, which contains plant remains. Two poorly preserved scales are figured in Plate XXXVI, figures 16 and 17.

Just as the Tertiary fishes mark an advance on the Mesozoic, so also the later Cretaceous fishes present evidence of evolution and modernization. This statement applies not only to the Upper as contrasted with the Lower Cretaceous, but also, and rather markedly, to the Montana group as contrasted with the Colorado group. The scanty materials from the Fox Hills and Pierre now available already indicate the beginnings of modern groups which are absent from the older beds, and unquestionably later discoveries will emphasize the distinctions observed. Thus we seem to find evidence of a rather slow and gradual modernization of the fish fauna, the breaks in the series corresponding with the geologic breaks and not being attributable to any extraordinary migrations or sudden new developments.

There were, however, certain environmental conditions which must have affected the rate of evolution and diversification. The inland seas of the American Paleozoic were drained by the Permian uplift, but during later Mesozoic time this country once more possessed a vast mediterranean sea, comparatively shallow and warm, which reached its maximum depth probably during the Niobrara epoch. A modern map of North America marked in some way to indicate the shallow-water areas, even down to 100 fathoms, will show how restricted is the distribution of the present littoral and shallow-water faunas. They exist, as it were, in broad rivers running mainly north and south. They are circumscribed by climate, by land, and by the open sea. In comparison the great Cretaceous inland sea must have afforded an amazing wealth of opportunity for multiplication and development, which may well have been the decisive factor in the evolution of many groups of marine organisms.

In this connection it is interesting to inquire whether there were radical differences between the supposedly contemporaneous faunas of Europe and America, and in America between the faunas of the Atlantic seaboard, the inland sea, and the Pacific coast. All these regions of course had types in common, and these appear to have been, at least principally, pelagic or open-sea organisms, such as *Uintacrinus* among the echinoderms and various sharks among the fishes. There were, however, many differences. Scales of fishes from the Chico, cut off from the inland sea by the western uplands, are all different from those in Rocky Mountain deposits. The Chico has a veritable clupeid, but so far no genuine clupeids have been found in the Benton, Niobrara, Pierre, or Fox Hills. The inland waters seem to have lacked berycoids, which are so characteristic of the European strata. Comparisons between the Old World and the New World faunas are hindered by the difference in age of some of the abundantly fossiliferous deposits. Not only do the highly differentiated faunas of Hakel and Sahel-Alma in Syria (Mount Lebanon) differ greatly from one another, but only about 10 per cent of their genera are common to the American Cretaceous. They must be referred to a later horizon than our Cretaceous fishes. The Cretaceous of Westphalia has more in common with the Syrian deposits than with the English chalk and should be intermediate in age between these two. Nearly half the genera of the English chalk are represented in the Kansas Niobrara, though perhaps the chalk is for the most part somewhat older. I have prepared more elaborate statistics, but owing to the uncertain standing of a good many of the species they are not as valuable as they look on paper. The tendency of future investigations will doubtless be to emphasize the differences in the faunas, especially as studies of scales are likely to reveal many of the smaller and more sedentary fishes.

Prof. J. Henderson, who has paid much attention to the Upper Cretaceous Mollusca, informs me that in his experience all the species of the Benton differ from those of the Niobrara, and all those of the Niobrara from those of the Pierre. The Pierre and Fox Hills, on the other hand, present faunas grading one into the other. As this did not wholly agree with some of the published records, I asked Mr. T. W. Stanton for his opinion. He replies that he is in perfect accord with Prof. Henderson. The

Colorado and Montana faunas had few if any identical species of Mollusca, though of course many genera occurred in both. Old records contrary to these opinions were based on errors. Thus *Inoceramus labiatus*, supposed to occur in the Niobrara of Kansas and Nebraska, was really from the Greenhorn limestone, well down in the Benton. We have, then, in the Upper Cretaceous two extremely marked faunal breaks. They must represent long periods, during which many things happened. Where no species of Mollusca persisted, surely no fishes could be expected to remain unaltered. Present information tends to confirm this opinion, and when a Benton fauna is found in beds ascribed to the Niobrara (see under *Holcolepis pulchellus*, p. 174) it is evident that there was an error in stratigraphy.

BENTON SHALE.

The previously recorded teleosts from the Benton are few, as follows:

Apsopelix. A genus not known from later rocks. Mr. Stanton informs me that Cope's locality (in Kansas) is certainly Benton.

Pelecorapis varius Cope. Mr. Stanton says almost certainly from the Benton; the *Inoceramus* referred to by Cope is presumably *I. labiatus*. Mr. Stanton adds, however, that if the Sibley referred to is the one now on the map there is some mistake, as this would place the locality in the Carboniferous.

Protosphyraena bentoniana Stewart.

Hypsodon lowii (Stewart). This and the last belong to genera common to the Niobrara and Pierre.

There is also a very dubious record of *Anogmius*. To these are added in the present paper the following species:

Holcolepis pulchellus [1] n. sp.
Holcolepis delicatus n. sp.
Holcolepis transversus n. sp.
Holcolepis obliquus n. sp.
Hypsodon? granulosus n. sp.
Ichthyodectes sp.
Leucichthyops vagans n. sp.
Erythrinolepis mowriensis n. sp.
Halecodon denticulatus n. sp.
Cimolichthys sp.

It is not at present certain that levels in the Benton can be distinguished by means of the fishes. Materials ascribed to the Aspen (for example, U. S. G. S. localities 4874, 3870) present a Mowry fauna, as they should, for the Aspen and Mowry are approximately equivalent.

NIOBRARA FORMATION.

The recorded fish fauna of the Niobrara is very rich, comprising 23 genera, mostly found in Kansas. Several of these are discussed below, but I have no new species to add.

MONTANA GROUP.

The Montana group includes the Pierre shale and Fox Hills sandstone. The fishes are not sufficiently well known to throw any particular light on the divisions of the group. The following new forms, the last three of which are from the Fox Hills sandstone, are described in this paper:

Petalolepis? fibrillatus n. sp.
Cycloides? incertus n. sp.
Hypsodon? radiatulus n. sp.
Echidnocephalus? americanus n. sp.
Helmintholepis vermiculatus n. sp.
Cyclolepis stenodinus n. sp.
Hemilampronites hesperius n. sp.

According to previous records about half a dozen Niobrara genera (*Hyposodon, Syllaemus, Protosphyraena, Ichthyodectes, Empo* or *Cimolichthys*, and perhaps *Pachyrhizodus*) survived to the Pierre; but not one of these is recorded from the Fox Hills. This means little, perhaps, as hardly anything has been known of the Fox Hills fishes.

CHICO GROUP.

The following species from the Moreno formation of the Chico group of California are described below:

Chicolepis punctatus n. sp.
Pomolobus? chicoensis n. sp.
Erythrinolepis chicoensis n. sp.
Echidnocephalus? pacificus n. sp.

DESCRIPTION AND SYSTEMATIC DISCUSSION OF SPECIES.

PISCES.

Subclass CHONDROSTEI.

Family ACIPENSERIDAE.

Scutes of *Acipenser* (*A. toliapicus* Woodward) are known from the London clay (lower Eocene) of the Isle of Sheppey. The plates named *A. cretaceus* Daimeries, from the Senonian of Belgium, are said by Woodward to belong apparently to some fish related to *Dercetis* or *Eurypholis*, and therefore are not chondrostean at all. In the Belly River formation (Upper

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[1] The rocks yielding this species were referred to the Niobrara by Beekly (U. S. Geol. Survey Bull. 596, pp. 40, 41, 1915), but the locality is in a faulted area and may well be on a Benton outcrop.

Cretaceous) of Red Deer River, Alberta, Lambe found a scute which he called *Acipenser albertensis*. In the same deposit he found part of an elongated snout which bore a series of teeth, much like that of the more ancient *Saurorhynchus* (*Belonorhynchus*). This he named *Diphyodus longirostris*, but he did not attempt to indicate its affinities. It was afterward stated by Hatcher [1] that remains similar to both these fossils were common in the Judith River and Lance formations in certain localities in Montana and Wyoming. The associated fossils indicated fresh-water conditions, so the absence of such remains from the Upper Cretaceous marine beds is not surprising. The question naturally arises whether by any possibility the *Acipenser*, so called, was in fact a toothed sturgeon, *Diphyodus* representing the jaw of the same fish. The Saurorhynchidae seem not to have survived to the Cretaceous (*Stenoprotome* Hay, from Syria, being a very dubious representative), but it is possible that toothed sturgeons more or less intermediate between the Saurorhynchidae and Acipenseridae existed in that period.

Subclass TELEOSTEI.

Order HALECOMORPHI.

Family PROTOSPHYRAENIDAE.

Protosphyraena Leidy (*Erisichthe* Cope) is abundantly represented in the Niobrara of Kansas and has one species each in the Benton and Pierre. It is known mainly by the rostra and pectoral fins, and there is in the descriptions no mention of scales. *Hypsocormus*, considered to be related to it, has smooth scales, small and deeply imbricating.

Order ISOSPONDYLI.

Family ALBULIDAE.

I have supposed that the Albulidae (*Albula* and *Dixonina*) were the only fishes above the Halecomorphi that had longitudinal basal circuli or fibrillae.[2] I find, however, that this peculiarity is shared by *Alepocephalus agassizi* (Alepocephalidae). *Benthosphyraena macroptera*, also referred to the Alepocephalidae, has small round scales wholly unlike those of *Alepocephalus*. The *Alepocephalus* scales, although having longitudinal basal fibrillae, are in other respects entirely different from those of the Elopidae, being shaped much like the sole of the foot, the nucleus subapical, with coarse concentric circuli above it, the lower margin broader and thin, neither crenulated nor with radii. The albulid scale, on the other hand, is subquadrate, with broad crenate lower margin and a few distinct basal radii. The albulid fibrillae are tuberculate, as in the Dipneusti; this is not true of *Alepocephalus*.

In view of their primitive characters, the Albulidae must have existed in the Cretaceous. The recorded species which have been assigned to this family, however, do not appear to belong there. *Prochanos* is to be referred to Chanidae. *Istieus* goes in Pterothrissidae. *Ancylostylos* from Croatia may be referred to a distinct family, of which it is the typical genus. *Anogmius* Cope (*Syntegmodus* Loomis), from the Niobrara of Kansas, may go in Pterothrissidae, but not in Albulidae or Osteoglossidae, to which it has been referred. *Plethodus* forms a family, Plethodontidae, to which Hay also refers *Anogmius*. *Apsopelix*, to judge from Cope's description of the scales, seems to have some resemblance to the Albulidae, where it is provisionally placed by Hay. Cope states that the circuli are vertical, except in the region of the nucleus. The position of this genus must for the present remain undecided. Finally, *Petalolepis divaricatus* (Geinitz), based on a scale from the Turonian of Saxony, appears to be a genuine albulid. An American scale is provisionally referred to the same genus.

Genus PETALOLEPIS Steinla.

Petalolepis? fibrillatus Cockerell, n. sp.

Plate XXXI, figure 1.

Scale 8.5 millimeters in diameter, subquadrate, but with obtusely rounded angles, a very little longer than broad; lines of growth evident, concentric, but the very fine fibrillae strictly longitudinal from one end to the other, except that toward the basal margin they curve inward, becoming more or less transverse, following the wavy outline of the margin; the fibrillae are not tuberculate or beaded, as they are in *Albula;* as in *Petalolepis divaricatus*, on each side of the middle line in the basal region the fibrillae become curved and end by meeting each other at a very acute angle; there is a strong median plica on the basal half of the scale, but no ordinary radii, and this agrees with *P. divaricatus*.

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[1] U. S. Geol. Survey Bull. 257, p. 69, 1905.

[2] U. S Bur. Fisheries Bull., vol. 32, p. 122, fig. 2, 1912.

U. S. G. S. locality 5094. Cretaceous, Mesa Verde formation, 14 miles north of Rock Springs, Wyo., a little east of center of sec. 26, T. 21 N., R. 104 W. (Collected by V. H. Barnett.)

A similar but much larger scale may represent a related species, but the surface as preserved presents a very fine irregular reticulation, with concentric lines of growth, and it can not be determined whether the fibrillae are longitudinal. So far as the visible characters go, this agrees with Winkler's problematic *Cycloides*, and it may provisionally stand as described below.

Cycloides? incertus Cockerell, n. sp.

Plate XXXI, figure 2.

Scale 16 millimeters in diameter (*C. incisus* Winkler is 17.5 millimeters in diameter), subquadrate; apical margin broadly rounded, apparently a little crimped; laterobasal angles obtuse but distinct; a very strong median plica on the basal three-fourths, the growth lines turned upward on approaching it, as in Winkler's figure.

U. S. G. S. locality 5177. Cretaceous, Mesaverde formation, about 5 miles southwest of Sycamore, Wyo., in the NE. ¼ sec. 12, T. 19 N., R. 103 W., in the Rock Springs region. (Collected by V. H. Barnett.)

In the general form and median plica this scale is suggestive of that of *Mugil curema*. The same sort of plica and basal margin may be seen in scales of the cyprinid *Cirrhina jullieni*. There is also a conspicuous median basal plica in *Chanos*, but it is broad and shallow, not forming a line.

Family LEPTOLEPIDAE.

A family found in the Cretaceous of Europe, surviving from the older Mesozoic. "Scales thin, cycloidal, and deeply imbricating, usually ganoid in their exposed portion; lateral line not observable." (A. S. Woodward.)

Family ELOPIDAE.

Genus HOLCOLEPIS Von der Marck.

This genus was called *Rhabdolepis* by Von der Marck in 1863, but Troschel had earlier (1857) used that name for a palaeoniscid fish. *Holcolepis* was proposed in 1868. Agassiz, who had proposed the name *Osmeroides* for an entirely different fish, unfortunately transferred it in 1844 to a species of *Holcolepis;* and in this he has been followed by several authors. The genus *Holcolepis* is certainly to be referred to the Elopidae, even after the removal of such genera as *Pachyrhizodus*, which A. S. Woodward places in that family. The teeth are minute, entirely different from those of *Pachyrhizodus*. The dorsal fin is less modified than in modern Elopidae. *Holcolepis* has not hitherto been reported from the North American Cretaceous, our nearest form being *Spaniodon simus* Cope, a form with smooth scales.

A. S. Woodward[1] described the scales of *Holcolepis* as "often ornamented in their exposed portion with delicate radiating lines of minute tubercles, marked in their covered portion with a few radiating grooves terminating in notches at the anterior truncated margin; hinder margin not serrated; course of lateral line indicated by a feeble ridge and a notch in the hinder border of most of the scales"—that is to say, the scales have basal radii; but in a later publication[2] Woodward shows a scale of *Osmeroides lewesiensis* (= *Holcolepis lewesiensis*) without any such radii.

Osmeroides divaricatus Geinitz, 1868, is based on the scales of an albulid fish, and takng up the name *Petalolepis* Steinla, published by Geinitz as a synonym, the species becomes *Petalolepis divaricatus*.

Osmeroides lewesiensis (Mantell) as determined by Geinitz from the Turonian of Saxony consists of a mixture of different things, none of them identical with the English fish. One, the most recognizable, is similar to the living genus *Pterothrissus* in the character of its scales. This form[3] unfortunately takes the cumbersome name *Kymatopetalolepis* of Steinla and may stand as *K. geinitzi* n. sp. It has four to six fanlike basal radii, the circuli between them broken into dots. The nucleus is subapical, and the apical region hyaline.

Osmeroides divaricatus Geinitz as figured by Fritsch[4] is wholly unlike the Geinitz species, having transverse basal circuli. There are three basal radii, and the basal margin is scalloped.

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[1] Catalogue of fossil fishes in the British Museum, pt. 4, p. 11, 1901.

[2] The fossil fishes of the English chalk, pl. 23, fig. 8, 1907.

[3] Geinitz, H. B., Die Fossilen Fischschuppen aus dem Plänerkalke in Strehlen: Gesell. Natur- u. Heilkunde Dresden Denkschr., 1868, pl. 2, figs. 10-12.

[4] Fritsch, Anton, Die Reptilien und Fische der böhmischen Kreideformation, fig. 58, 1878.

O. lewesiensis (Mantell) of Fritsch is also wrongly named. It is a scale with subapical nucleus and five strong basal radii, the basal margin very strongly scalloped. The scale has a strong resemblance to that of *Megalops cyprinoides*, and may therefore represent a fossil elopid of some unknown genus.

Osmeroides belgicus Winkler, 1874, is based on a scale apparently congeneric with the so-called *lewesiensis* of Fritsch but considerably broader and with more basal radii. It is a large scale, the transverse diameter being 15 millimeters.

The type of *Holcolepis*, *H. cretaceus* Von der Marck, is imperfectly known, and it is possible that the various species supposed to be congeneric could be divided into two genera with better materials. For the present I assume that the scale of *H. lewesiensis*, well figured by Woodward, is typical of the genus. Its most characteristic feature is the pseudoctenoid exposed area, ornamented with radiating lines of pustuliform markings, derived from the circuli. *H. latifrons* (Woodward), from the chalk of Kent, is similarly ornamented, but the lines are more broken up, producing, except near the margin, a pitted or malleate effect. The lateral line is very distinct. In *H. levis* (Woodward), from the chalk of Kent and Sussex, the scales possess "fine radiating ornament" and have distinct basal radii. They are therefore similar to those of the modern *Elops*, and the fish may not be congeneric with the others.

The modern Elopidae (*Elops*, *Tarpon*, *Megalops*) have very distinct basal radii, 3 in *Tarpon*, about 5 to 7 in *Megalops*, and 12 to 18 in *Elops*. The basal margin is very strongly crenate in *Megalops*, moderately in *Tarpon*, but feebly in *Elops*. In *Tarpon* the apical field has a radiating sculpture of minute tubercule-like elements, not clearly visible on casual inspection. This is the *Holcolepis* sculpture, but very much finer and less conspicuous. In *Megalops* the region above the nucleus shows granulations but not distinct radial lines; there is some approach to the condition of *Holcolepis latifrons*. *Elops*, above the nucleus, shows coarse transverse wrinkled lines, but the broad apical field is free from markings derived from the circuli and presents a number of parallel radii. Apparently, then, the early elopids (*Holcolepis*) had the exposed part of the scale prominently sculptured with lines or rows of tubercles derived from the circuli, while the covered part was either without evident sculpture, except the fine circuli, or had a few distinct radii. The development has been toward the loss of the apical sculpture and the strengthening and increase in number of the basal radii. It seems that these changes were in process or even perfected as early as the Cretaceous, but typical *Holcolepis*, as here understood, included the more primitive type. *Pachyrhizodus*, to judge from the figure of a scale of *P. subulidens* (Owen) published by Woodward (reproduced in Pl. XXXII, fig. 3), had scales of the *Holcolepis* type, with strong or coarse sculpture on the exposed portion, and the base rounded and without radii. The scale was parallel-sided, and longer than broad, the reverse being true of typical *Holcolepis*. Thus, though we may well place *Pachyrhizodus* in a distinct family, it may have had a common ancestor with the elopids, possessing the *Holcolepis*-like scale.

In the American Cretaceous fauna the species described below, based on scales, are referred to *Holcolepis*, as understood in a rather broad sense. Outside of the Elopidae the scales show a certain general resemblance to those of *Aulopus* (Aulopidae), but in that genus the margin is strongly dentate.

Holcolepis pulchellus Cockerell, n. sp.

Plate XXXI, figures 3, 4.

Scale 7 millimeters in diameter, approximately circular, the apical margin obtusely angulate in the middle; nucleus only a little above the middle; lower margin not at all crenate; six or seven basal radii very feebly indicated, not distinctly developed, not definitely cutting the circuli; apical field with very numerous parallel raised lines, but toward the nucleus with wavy lines as in *Elops*.

One mile south of the Boetcher ranch, in the NE. ¼ SW. ¼ sec. 32, T. 10 N., R. 81 W., North Park, Colo. (Collected by A. L. Beekly and Harvey Bassler.) This is Beekly's locality 37.[1] It is referred to the Niobrara, but the scales from this and several other localities referred by Beekly to the Niobrara resemble those from the Mowry and are therefore believed to have come from the Benton shale. All the localities thus under suspicion failed to yield any characteristic Niobrara Mollusca, and the collection from Beekly's locality 59, which did include *Ostrea congesta* Conrad, offered no such scales, but only one of *Ichthyodectes*, the so-called "*Cladocyclus*."

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[1] Beekly, A. L., U. S. Geol. Survey Bull. 596, p. 42, 1915.

H. pulchellus was also found on the northwest shore of Lake John, in the SE. ¼ SW. ¼ sec. 34, T. 10 N., R. 81 W., North Park, Colo., by Beekly and Bassler. This is Beekly's locality 35.

Holcolepis delicatus Cockerell, n. sp.

Plate XXXI, figure 5.

Scale 10 millimeters in diameter, subcircular, similar to *H. pulchellus*, but apical margin rounded, nucleus a little below the middle; lines of exposed area finer and denser, with more or less evident pits between; only vague indistinct suggestions of basal radii.

Big Horn Basin, in the SE. ¼ SE. ¼ sec. 15, T. 43 N., R. 94 W., Wyoming. Near base of Mowry shale. (Collected by C. T. Lupton.)

Holcolepis transversus Cockerell, n. sp.

Plate XXXI, figures 6-13.

Scales subquadrate, on sides nearly twice as broad as long, on other parts often narrow, varying to about as broad as long; laterobasal angles commonly rather prominent; apical margin broad, flattened or depressed in middle, not angular; no basal radii, but often a single median fold, rather indistinct; apical modified patch V-shaped, ornamented with a series of closely set interrupted ridges, without pits between; circuli fine, the lateral ones directed upward, meeting the margin at a very acute angle; nucleus approximately central.

Type a scale 9 millimeters in diameter, from U. S. G. S. locality 6682, Slate Creek, Mount Leidy quadrangle, Wyo. (Collected by Eliot Blackwelder.) Mollusks of this locality are said to be not characteristic and may belong either in the Montana group or the upper part of the Colorado group, but the fish scales indicate Colorado (Benton) age. Other scales in the same lot, referred to this species, are 11 millimeters and 14 millimeters in diameter.

I also refer to this species the following:

U. S. G. S. locality 6681. Cretaceous, probably Aspen, Slate Creek, Mount Leidy quadrangle, Wyo. (Collected by Eliot Blackwelder.) Scale 10.5 millimeters in diameter.

U. S. G. S. locality 6713. Cretaceous, Mowry shale, southeast of camp at old chimney, Sisters Hill, Buffalo, Wyo. (Collected by O. B. Hopkins.) Scale 9 millimeters long and 11 millimeters wide; another scale 7 millimeters wide.

The two following specimens are about as broad as long and probably came from the vicinity of the caudal peduncle.

U. S. G. S. locality 4421. Mowry shale, Casper region, sec. 29, T. 33 N., R. 74 W. sixth principal meridian, Wyoming. (Collected by E. W. Shaw.) Scale 12.5 millimeters in diameter.

U. S. G. S. locality 3417. Lower (Benton) part of Mancos shale, Steamboat Springs, Routt County, Colo., on ridge near mineral springs, just west of town and south of Yampa River. (Collected July 13, 1905, by T. W. Stanton and H. S. Gale.)

Holcolepis transversus is closely related to *H. steinlai* (Geinitz), published by Geinitz as *Acrogrammatolepis steinlai*, the figure upside down. The *H. steinlai* scale is 7 by 6 millimeters and has the nucleus apparently more basally placed than in *H. transversus*. It is from the Turonian of Saxony and may very likely be identical with the English *H. lewesiensis* (Mantell), from beds of about the same age.

Holcolepis obliquus Cockerell, n. sp.

Plate XXXII, figure 1.

Scales 10 millimeters in diameter, much broader than long, without any trace of basal radii. Similar in most respects to *H. transversus*, but remarkable for the brevity of the elements in the apical patch and for the lateral circuli being oblique, at the middle of the side reaching the margin at an angle of about 45°, and above this becoming almost transverse.

Type collected with *H. transversus*, in Mowry shale at U. S. G. S. locality 4421. Details are given above.

Holcolepis? mandible.

Plate XXXII, figure 2.

In confirmation of the existence of a typically elopid type of fishes in the North American Cretaceous, I give a figure of a mandibular ramus which seems to belong to *Holcolepis* or a closely related genus. It differs from that of *H. lewesiensis* in the straight (not concave) descending upper margin of the dentary, and in this respect more resembles the modern *Elops*.

It was collected by A. C. Veatch in the NW. ¼ SW. ¼ sec. 8, T. 19 N., R. 79 W., Carbon County, Wyo., and is ascribed to the Colorado group. From the associated scales, which include an imperfect specimen of *Holcolepis*, either *pulchellus* or a closely related species, I infer that the material is from the Benton. The mandible and the *Holcolepis* scale probably belong to the same species.

Genus RHACOLEPIS Agassiz.

Dr. D. S. Jordan has kindly sent me material of *Rhacolepis buccalis* Agassiz, from the Cretaceous of Ceara, Brazil. The scales are broad, with coarse, rather widely spaced circuli, transverse above and below the nucleus, and many of them broken or anastomosing above the nucleus. The apical margin is delicately plicate, with a series of parallel ridges, very much as in *Ctenothrissa*. This marking probably corresponds with the system of apical radii of *Elops* and has nothing to do with the pseudoctenoid sculpture, derived from the circuli, of *Holcolepis*. *Rhacolepis* is therefore entirely distinct from *Holcolepis*, and the scales can not be confused. It is just possible that the *Pachyrhizodus* scale, which seems from Woodward's figure (reproduced in Pl. XXXII, fig. 3) to be of the same general type as that of *Holcolepis*, is really constructed in the manner of *Rhacolepis*, but with the shape entirely different and the apical plicae much longer.

Genus NOTELOPS Woodward.

In the Brazilian Cretaceous *Notelops brama* (Agassiz), also received from Dr. Jordan, the circuli are finer and denser than in *Rhacolepis*. I can not make out any "delicate radiating ridges," mentioned by Woodward, but the material is not very good. Jordan and Branner[1] state that the scales are cycloid and entire. They are, in any event, wholly distinct from those of *Rhacolepis*.

Genus HELMINTHOLEPIS Cockerell, n. gen.

Scale cycloid, circular, or slightly longer than wide, about 17 millimeters across in the type; nucleus a little below the middle; circuli fine, concentric on basal half but longitudinal and very wavy, like minute worms, on apical half; the apical marginal area delicately longitudinally striate, with about five circuli between each pair of striæ or fine radii. This may not be elopid, but I do not know where better to refer it. The striate margin is like that of *Hypsodon*, but there are no tubercles, and the microscopic structure is very different. There are no radii in the basal field, and the lower margin is broadly rounded. Type *H. vermiculatus*.

Helmintholepis vermiculatus Cockerell, n. sp.

Plate XXXII, figure 4.

Diameter about 17 millimeters.

U. S. G. S. locality 9184, Cretaceous, Fox Hills sandstone, north side of Thompson River, near top of ridge about 1½ miles northeast of Milliken, sec. 1, T. 4 N., R. 67 W., Greeley quadrangle, Colo. (Collected by T. E. Williard.) The type scale partly overlaps a scale of *Hemilampronites hesperius*.

Family PTEROTHRISSIDAE.

The interesting family Pterothrissidae is represented to-day by *Pterothrissus* Hilgendorf (*Bathythrissa* Guenther) from deep water off Japan. It is related to the albulids, but the scales have the circuli of the median and basal regions (a large inverted V-shaped area) broken up into dots and fine rugae. In the Cretaceous rocks of Westphalia and Syria the family is represented by the genus *Istieus*, the scales of which are said to be elliptical, not pectinated (A. S. Woodward). *Anogmius*, from the Niobrara of Kansas, seems to be more or less related. *Kymatopetalolepis geinitzi* Cockerell, based on scales from the Turonian of Saxony, appears to be typically pterothrissid. *Chicolepis*, a new genus from the Chico, may also be referred to this family.

Genus CHICOLEPIS Cockerell, n. gen.

Scales broad, subquadrate, shaped as in *Pterothrissus*, with very broadly rounded apical margin; nucleus apical, very near the margin; sides with dense simple longitudinal circuli, passing vertically up to the apical margin; the whole area inclosed by lines drawn from the middle of the apex to the laterobasal corners is covered with minute punctiform dots, the circuli having combined to form an extremely dense honeycomb-like reticulation, the punctures round and often running more or less in transverse series. In the region of the lateral circuli are here and there streaks of punctured surface. No ordinary radii, but a median line or plica from base to apex, most conspicuous on basal half. This superficially resembles *Petalolepis? fibrillatus*, but its structure is very different. Type, *C. punctatus*.

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[1] Smithsonian Misc. Coll., vol. 52, p. 9, 1908.

Chicolepis punctatus Cockerell, n. sp.

Plate XXXIV, figure 1.

Scale 16 millimeters in diameter; laterobasal corners rectangular.

U. S. G. S. locality 7030. Cretaceous, Chico group, south side of Ortigalito Creek, Cal., in Moreno formation. (Collected by Robert Anderson.) For further description of locality see *Pomolobus chicoensis*. The absence of the ordinary radii at once distinguishes this species from *Pterothrissus* and *Kymatopetalolepis*.

Family ICHTHYODECTIDAE.

The fishes assigned to the Ichthyodectidae can not be referred to Chirocentridae; the scales are radically and entirely different from those of the living *Chirocentrus*, and the teeth are implanted in deep sockets. Stewart also seems fully justified in separating the Saurodontidae, especially on account of the remarkable unpaired predentary.

Genus HYPSODON Agassiz.

The type of *Hypsodon* is *H. lewesiensis*, but unfortunately Agassiz included under this name fishes that were not even congeneric. Cope, commenting on this fact, remarked that *Hypsodon* included some fishes with teeth of equal length and others in which they were unequal. He proposed to restrict the name to the genus having equal teeth, and according to this decision *Hypsodon* would take the place of the genus later named *Pachyrhizodus* by Dixon. However, the specific name *lewesiensis* was adopted from Mantell, who had described the fish with unequal teeth as *Megalodon? lewesiensis*. It is this fish which Agassiz figured in "Recherches sur les poissons fossiles," volume 5, Plate XXVa, figure 3, and Plate XXVb, figures 1–3. This appears to fix the type in a contrary sense to Cope's decision, and *Hypsodon* takes the place of *Portheus* Cope. Stewart suppressed *Portheus* in favor of *Xiphactinus* Leidy, which was based on a pectoral fin spine of the same species as Cope's type of *Portheus*. *Hypsodon* is much older, and the giant fish of the Niobrara rocks will take the name *Hypsodon audax* (Leidy). *Portheus mantelli* Newton, from the English chalk, becomes *Hypsodon lewesiensis* (Mantell). In America the genus is well represented in the Niobrara and has one species, *Hypsodon lowii* (*Portheus lowii* Stewart), in the Benton.

The University of Kansas has remarkably well preserved material of *H. audax*, and through the kindness of Prof. S. J. Hunter I have received photographs of the scales, which are reproduced here.

Hypsodon audax (Leidy) Cockerell.

Plate XXXII, figure 8; Plate XXXIII, figures 1, 2.

Xiphactinus audax Leidy, Acad. Nat. Sci. Philadelphia Proc., p. 12, 1870; U. S. Geol. Survey Terr. Rept., vol. 1, pp. 290, 348, pl. 17, figs. 9, 10, 1873.
Cope, U. S. Geol. Survey Terr. Rept., vol. 2, p. 276, 1875.
Hay, Zool. Bull., vol. 2, p. 27, 1898.
Stewart, Kansas Univ. Quart., vol. 7, p. 115, 1898; idem, vol. 8, p. 107, 1899; Kansas Univ. Geol. Survey, vol. 6, p. 267, pls. 33–47, 1900.
Saurocephalus audax (Leidy) Cope, Am. Philos. Soc. Proc., vol. 11, p. 553, 1870; U. S. Geol. Survey Terr. Ann. Rept. for 1870, p. 418, 1871.
Portheus? audax (Leidy) Hay, U. S. Geol. Survey Bull. 179, p. 384, 1902.

Scales extremely broad, the width about twice the length, though on the caudal peduncle they are undoubtedly much narrower. Exposed area densely covered with small tubercles, which in the apical region are arranged in longitudinal series, being in fact situated on longitudinal ridges. The basal region has fine concentric lines of growth, and numerous more or less broken radii, spread out in broad fan shape. The *Cladocyclus occidentalis* of Leidy, which has page priority over *Xiphactinus audax*, is based on just such scales, but whether of the species *H. audax* it is not at present possible to decide. Loomis thought the *C. occidentalis* scales belonged to *Ichthyodectes* (or *Gillicus*) *arcuatus* Cope, and wrote *Ichthyodectes occidentalis* (Leidy) for that species. This assignment certainly can not be maintained. It appears that the type locality of *C. occidentalis* is uncertain: On one page Leidy says that the material came from Nebraska; on another he says that it came from Sage Creek, Dakota. Leidy suggested that the scales before him probably belonged to several species.

The name *Cladocyclus* Agassiz was based on scales from Brazil (*C. gardneri* Agassiz), which do not appear to be identical with any of the North American or European genera, though there is close similarity in the branching lateral line canals. I have material of the Brazilian fish, kindly sent by Dr. D. S. Jordan. Woodward, in his "Fossil fishes of the English chalk," abandons the use of *Cladocyclus* for European fishes, remarking that Agassiz referred to this genus scales of the *Ichthyodectes* type, calling them all *Cladocyclus lewesiensis*. The scales which Geinitz called *Cladocyclus strehlensis* were in the main of this same type.

The question which now arises is whether scales of *Hypsodon* can be clearly distinguished from those of *Ichthyodectes*. Woodward figures *Ichthyodectes* scales, and they differ from those of *Hypsodon* only in the strictly entire basal radii. In *Ichthyodectes*, as I understand it, the basal part of the scale frequently splits along the radii, producing the appearance of a frayed edge of separated narrow bands. The lateral line canal is branched, more or less Y-like, or rarely in the complex manner of the Brazilian *Cladocyclus*. A photograph of "*Cladocyclus lewesiensis*," received from Dr. A. S. Woodward, shows the fraying-out effect very well and should represent *Ichthyodectes*. The species of *Hypsodon* and *Ichthyodectes* recorded from the Kansas Niobrara are numerous, and it will be difficult or impossible to connect them all up with their scales.

A very fine scale, 40 millimeters long and 35 millimeters broad, comes from the Niobrara of New Mexico (U. S. G. S. locality 8354, Meloche ranch, eastern edge of Raton quadrangle; collected by W. T. Lee). It is not at all of the same shape as the Kansas University *H. audax* scales, but it presumably comes from the caudal region, and is similar to one of the scales figured by Leidy as *Cladocyclus occidentalis*. The striae in the apical region are very delicate, and the tubercles are between the ridges instead of upon them; but this is probably a reverse impression. In view of the large size and general agreement in characters this scale is referred to *H. audax*.

A still larger *H. audax* scale comes from Wyoming (10 miles southeast of Glenrock, in the SW. ¼ NE. ¼ sec. 29, T. 33 N., R. 74 W.; collected by V. H. Barnett); it is 51 millimeters across.

Typical *H. audax* scales, about 50 millimeters across, have been found in the Mancos shale 1½ miles northeast of Columbine, Routt County, Colo. (Collected by Colorado Geological Survey.)

Hypsodon lowii (Stewart) Cockerell.

Plate XXXIV, figure 2.

Portheus lowii Stewart, Kansas Univ. Quart., vol. 7, p. 24, pl. 2, fig. 2, 1898.
Hay, U. S. Geol. Survey Bull. 179, p. 384, 1902.
Xiphactinus lowii (Stewart) Hay, Zool. Bull., vol. 2, p. 27, 1898.
Stewart, Kansas Univ. Geol. Survey, vol. 6, p. 293, pl. 48, fig. 2, 1900.

U. S. G. S. locality 7294. Cretaceous, Benton, sec. 20, T. 9 N., R. 77 W., half a mile northwest of Kerr's ranch, North Park, Colo. (Collected by A. L. Beekly and Harvey Bassler.) A large scale, 32 millimeters across, provisionally referred to *H. lowii*, as it is exactly the sort of scale that species might be expected to have.

Hypsodon? radiatulus Cockerell, n. sp.

Plate XXXII, figures 6, 7.

Scale 15 millimeters across, with apical ridges but apparently without the tubercles of *H. audax*. Another scale, 15.5 millimeters across, is of the same species but latinucleate (renovated). As this species comes from a later formation than the Niobrara, it is doubtless distinct from the Kansas fishes described.

U. S. G. S. locality 5177. Cretaceous, Mesa Verde, about 5 miles southwest of Sycamore, Wyo., in the NE. ¼ SE. ¼ sec. 12, T. 19 N., R. 103 W., in the Rock Springs region. (Collected by V. H. Barnett.) *Cycloides? incertus* is from the same locality and horizon.

U. S. G. S. locality 5174. Cretaceous, Mesa Verde, about 2½ miles north of Sycamore, Wyo., in the SE. ¼ sec. 17, T. 20 N., R. 102 W.

Hypsodon? granulosus Cockerell, n. sp.

Plate XXXII, figure 5.

Scale nearly circular, slightly broader than long, about 21 millimeters in diameter, basal and apical margins rounded; circuli fine, concentric, except in large exposed area extending to the region of the nucleus in the center of the scale, where the surface is finely rugose, without the definite tubercles of *H. audax;* apical margin longitudinally striate but not tuberculate;

base with about a dozen imperfect and broken radii.

U. S. G. S. locality 4874. Cretaceous, Mowry shale, 100 double paces south of the north quarter corner of sec. 19, T. 28 N., R. 91 W., near North Rawlins, Wyo. (Collected by O. P. Hopkins.)

It is possible that this species and *H.? radiatulus* belong to elopid fishes, and not to the Ichthyodectidae. With *H.? granulosus* occurred *Leucichthyops vagans* and *Holcolepis transversus.*

Genus ICHTHYODECTES Cope.

Plate XXXIV, figures 3, 4.

About eight species of *Ichthyodectes* are known from the Niobrara of Kansas. Three species occur in the chalk of England. The type species is *I. ctenodon* Cope from Kansas. At present we can do no more than recognize the genus from the scales; it is doubtful whether the scales exhibit specific characters. The two following are characteristic:

U. S. G. S. locality 2402. Cretaceous, lower part of Colorado shale, creek north of Lower Sherburne Lake, Swift Current Valley, tributary to St. Marys River, Mont., latitude 48° 50–55′, longitude 113° 25′. (Collected by Bailey Willis and Stuart Weller.) Scale 6 millimeters in diameter.

U. S. G. S. locality 7277. Cretaceous, Niobrara, in the NE. ¼ SE. ¼ sec. 34, T. 7 N., R. 82 W., east of Clover Valley telephone line, about 3 or 4 miles south of Butler, North Park, Colo., yellow sandy material. (A. L. Beekly.) This is Beekly's locality 59.[1] *Ostrea congesta* occurred in the same material.

Ichthyodectes scales also occur in Benton rock north of Boulder, Colo., where they were collected by Prof. J. Henderson (Colorado Univ. Mus. 459). One of these scales, 15 millimeters in transverse diameter and about 11 millimeters long, is from the lateral line and is remarkable for the complex, treelike system of branching canals, quite as complex as in the Brazilian *Cladocyclus.* This species tends to weaken our conviction that *Ichthyodectes* and *Cladocyclus* are really different genera; but the scales of *Cladocyclus gardneri* differ in the basal region from those of *Ichthyodectes*, and in view of the difference of locality there is no great probability that the fishes are really congeneric. Moreover, as A. S. Woodward shows, *C. gardneri* differs also from *Ichthyodectes* in the more anterior position of the dorsal fin.

Ichthyodectes libanicus (Pictet and Humbert), from Syria, which I have examined in the American Museum of Natural History, has very broad scales, smooth and porcelain-like on their exposed parts. Woodward states that the species has the dentition of *Ichthyodectes.*

Cretaceous fish scales from Turkestan.

Plate XXXIV, figures 6-12.

G. D. Romanowsky [2] has figured certain Cretaceous scales from Turkestan, and the figures are reproduced on Plate IV.

Figures 6, 7, 8, referred by Romanowsky to *Cladocyclus strehlensis* Geinitz, agree with *Hypsodon.*

Figure 9, referred to *Osmeroides lewesiensis* var., appears to be immature *Hypsodon*, the scale probably from the subcaudal region.

Figure 10, referred to *Cladocyclus strehlensis*, agrees with *Ichthyodectes.*

Figure 11, called *Osmeroides pectinolepis* Romanowsky, is imperfect and apparently latinucleate (regenerated); it may be *Ichthyodectes.*

Figure 12, called *Beryx* sp., can not be determined. It shows nothing to justify a reference to the genus *Beryx.*

Family PLETHODONTIDAE.

The scales of *Plethodus* are unknown; the species are distinguished by the form of the dental plates. *Anogmius* Cope, well represented in the Niobrara of Kansas, is placed in the Plethodontidae by Woodward and Hay. Its former reference to the Osteoglossidae was manifestly incorrect; no Cretaceous Osteoglossidae are known, nor are they likely to be found in marine strata. The scales of *Anogmius polymicrodus* Stewart, as described by A. S. Woodward, are "moderately thick, showing only lines of growth; they appear to have been deeply overlapping."

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[1] U. S. Geol. Survey Bull. 596, p. 42, 1915.

[2] Materialui dlya geologii Turkestanskago kraya, pts. 2, 3, 1884, 1890.

Family CLUPEIDAE.

Genus POMOLOBUS Rafinesque.

Pomolobus? chicoensis Cockerell, n. sp.

Plate XXXIV, figure 5.

Scales 4.2 millimeters broad, considerably broader than long, cycloid, with the hyaline apical margin at most slightly crimped; covered portion with very fine strictly transverse circuli; a more or less distinct median longitudinal groove or fold on basal half; three transverse radii, the second and third interrupted in middle, the interval a little greater than half the length of either lateral division.

U. S. G. S. locality 7030. Cretaceous, Chico group, south side of Ortigalito Creek, Cal., 1 mile above the mouth of its canyon and 1¼ miles northeast of Erreca's, in base of gully draining north along west line of the SW. ¼ sec. 28, T. 11 S., R. 10 E., and joining Ortigalito Creek near center of west line of section. In shale of Moreno formation, below the fossiliferous conglomerate. (Collected by Robert Anderson.)

This scale exactly agrees with the living genus *Pomolobus*, differing from *P. pseudoharengus* (Wilson), from Lake Ontario, only in the directly transverse, not distinctly oblique broken radii. It is very likely that other parts of the fish would reveal generic distinctions, but perhaps it is not impossible that *Pomolobus* dates from the Upper Cretaceous. It is a singular thing that such a type should be found in the California Chico but should wholly fail to appear (so far as my material shows) in the strata east of the Sierra Nevada, whereas to-day *Pomolobus* and its close relative *Alosa* are found only in the north Atlantic and (*Alosa*) Mediterranean. With reference to the antiquity of the clupeid type, it may be noted that A. S. Woodward[1] describes a fish from the Lower Cretaceous of Bahia, Brazil, as *Scombroclupea scutata*, and remarks that it does not differ much from *Clupea* itself. Typical *Scombroclupea* comes from the much later rocks of Mount Lebanon, in Syria, and it is very probable that the Brazilian fish, when better known, will prove generically distinct. In the North American Cretaceous we have recorded only one supposed clupeid type, *Syllaemus* Cope (*Leptichthys* Stewart). I have examined scales of *Syllaemus latifrons* Cope, the type of the genus, and the circuli are not transverse, as in Clupeidae.[2]

Family SALMONIDAE.

Genus LEUCICHTHYOPS Cockerell, n. gen.

Scales similar in type to those of the living *Leucichthys nigripinnis* (Gill); cycloid, the apical margin broadly rounded, the basal with a broad median lobe, the margin more or less concave between this and the rather prominent laterobasal angles; apical radii weak, about as in *Leucichthys;* no basal radii; circuli fine, concentric; growth lines very distinct, probably indicating that the fish was migratory. Scales from caudal region are narrower. Lateral line scales have a prominent canal, expanding basally. Type *L. vagans*.

Leucichthyops vagans Cockerell, n. sp.

Plate XXXIV, figure 13; Plate XXXV, figures 1–15.

The type scale is from U. S. G. S. locality 7095 and has a diameter of 9 millimeters. It is distinctly broader than long. The exact locality is the NW. ¼ SW. ¼ sec. 20, T. 11 N., R. 79 W., 1 mile southwest of Dean's ranch, North Park, Colo. This is Beekly's locality 19, supposed to be Niobrara but to judge from the fishes apparently Benton. The following are also referred to this species, although they may represent more than one species, not readily if at all separable on scale characters. The scales differ greatly in shape, but only as might be expected on different parts of the fish.

1. Scales of the same general form as the type.

Colorado group, in the NW. ¼ SW. ¼ sec. 8, T. 19 N., R. 79 W., Carbon County, Wyo. Scale 12.50 millimeters long and broad. Also second scale, incomplete.

U. S. G. S. locality 3880. Near base of Mancos shale, 4 miles east of Meeker. Colo. Scale 11 millimeters in diameter.

Graneros shale, Little Spring Creek, northeast corner of Sturgis quadrangle, Black Hills, in reddish rock. In addition to normal scales there is a large latinucleate (regenerated) one 13 millimeters in diameter.

U. S. G. S. locality 7275. Lower Benton, north bank of Norris Creek about 200 yards north of Norris house, 12 to 14 miles south of Walden, in the NE. ¼ SW. ¼ sec. 13, T. 8 N., R. 82 W., North Park, Colo. (Collected by A. L. Beekly.) This is Beekly's locality 57.[1] A large scale, diameter 14.5 millimeters.

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[1] London Geol. Soc. Quart. Jour., vol. 64, p. 360, 1908.

[2] Zool. Anzeiger, Band 45, p. 190, 1914.

2. Narrow scales, presumably from the caudal peduncle.

U. S. G. S. locality 6681. Probably Aspen, Slate Creek, Mount Leidy quadrangle, Wyo. (Collected by Eliot Blackwelder.) Scale about 9 millimeters across, distinctly convex. *Holcolepis transversus* occurs at the same locality and horizon.

U. S. G. S. locality 7110. Probably Benton, Beekly's locality 37.[2] Scale 8.2 millimeters across. *Holcolepis pulchellus* occurs at the same locality and horizon.

U. S. G. S. locality 8916. Mowry shale, Big Horn Basin, Wyo. (Collected by C. T. Lupton.) For exact data see description of *Holcolepis delicatus* (p. 175), which occurred with it. The narrow *Leucichthyops* scale is accompanied by others of the normal type.

3. Broad, lateral line scales.

U. S. G. S. locality 6682. Cretaceous, probably Colorado group, Slate Creek, Wyo. (Collected by Eliot Blackwelder.) Accompanied by a typical scale of the same species and by scales of *Holcolepis transversus*.

U. S. G. S. locality 7095. Probably Benton, in the NW. ¼ SW. ¼ sec. 20, T. 11 N., R. 79 W., 1 mile southwest of Dean's ranch, North Park, Colo. This is Beekly's locality 19, the type locality of *L. vagans*. Narrow scales also occur. There is also a scale of *Holcolepis obliquus*.

U. S. G. S. locality 7100. In the NW. ¼ SE. ¼ sec. 8, T. 11 N., R. 81 W., northeast of the Hill ranch, North Park, Colo. Beekly's locality 26,[2] said to be Niobrara but probably Benton. (Collected by A. L. Beekly and G. J. Finlay.) The scale is 8 millimeters in diameter and is accompanied by a typical scale and one of *Holcolepis*.

U. S. G. S. locality 7110. Beekly's locality 37 (see above).

The scales of *Leucichthyops* certainly appear to indicate a primitive salmonid fish; the bones were probably delicate and rarely preserved. The scales show a certain resemblance, however, to those of *Thymallus*, though in that genus the lateral line scales are much narrower and the median basal lobe is very large. It is, of course, possible that in the Cretaceous the Salmonidae and Thymallidae were not differentiated. None of the European scales figured by Geinitz or Fritsch are of the *Leucichthyops* type. The scales of *Aulolepis typus* Agassiz, as figured by Woodward,[3] are curiously similar to those of *Leucichthyops* but wholly lack the radii in the apical field.

Genus CYCLOLEPIS Geinitz.

The name *Cyclolepis* has been applied to subcircular or oval scales, with concentric circuli, nucleus central or subcentral, and all radii and ctenoid elements wholly absent. This is, of course, the salmonid type of scale, excellently typified by the living *Stenodus mackenziei*, from Alaska. *Caranx* scales are very similar but have the circuli more or less distinctly angular at the sides. The scale which Fritsch erroneously calls *Aspidolepis steinlai* Geinitz, from the Cretaceous of Bohemia, has the shape and moderately eccentric nucleus exactly as in *Stenodus*. A difficulty in dealing with scales of this simple type is that uncharacteristic scales of quite different fishes may closely simulate them, as shown by H. F. Taylor[4] in figures of essentially cycloid scales from the head of *Cynoscion*. Of course, the more characteristic scales of the same fishes would be almost sure to appear also in the deposits.

Cyclolepis stenodinus Cockerell, n. sp.

Plate XXXV, figure 16.

Scale oval, its greater diameter 12 millimeters; nucleus central (not eccentric as in *Stenodus*); circuli simple and concentric; rather strong growth lines, indicating possible migratory habits. Another scale, doubtless of the same species, is practically circular.

U. S. G. S. locality 9190. Fox Hills sandstone, Greeley quadrangle, Colo. (Collected by T. E. Williard.) For details of the locality, see description of *Hemilampronites hesperius* (p. 185), which was found with it. The mollusk *Callista nebrascensis* Meek and Hayden was in the same material.

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[1] U. S. Geol. Survey Bull. 596, p. 38, 1915.

[2] Idem, p. 42.

[3] Woodward, A. S., The fossil fishes of the English chalk, pl. 19, figs. 3b, 4, 1903.

[4] U. S. Bur. Fisheries Bull., vol. 34, pl. 52, 1914.

Family ERYTHRINOLEPIDAE Cockerell, n. fam.

Genus ERYTHRINOLEPIS Cockerell, n. gen.

Scales rather small, subtriangular or subcircular, cycloid; basal margin slightly or not crenate; circuli normal and concentric on basal half but excessively fine on apical half; radii apical, basal and lateral, but very irregular and often broken. The scales closely resemble those of the South American fresh-water Erythrininae but lack the coarse vertical circuli of the apical area. They may also be compared with the Old World Cyprinidae, and more remotely with the African fresh-water genus *Phractolaemus*. They also show some resemblance to *Pantodon*.[1]

While I was puzzling over the scales, I received a paper by Eastman [2] in which it is set forth that the Cretaceous teeth of the genus *Onchosaurus* Gervais (*Ischyrhiza* Leidy; *Gigantichthys* Dames) agree very closely with those of the living fresh-water *Hydrocyon* and *Hoplias*, characoid genera.[3] It appeared to be a confirmation of Eastman's results that fish scales so similar to those of the Erythrininae (*Hoplias*, *Hoplerythrinus*, and *Erythrinus*) should occur in the Mowry shale. I wondered whether the Mowry could be a fresh-water deposit; and this suspicion seemed to receive some confirmation in the collection from U. S. G. S. locality 6603, in the Uinta Basin, Utah, assigned to the Mowry and including poorly preserved remains of land plants. This lot, however, included no *Erythrinolepis* scales. Mr. Stanton informed me that although Mollusca were rarely found in the Mowry, two localities on the southeastern border of the Big Horn Mountains had yielded ammonoids probably belonging to the genus *Metoicoceras*, and one of them yielded *Inoceramus*. These are clearly marine. One of these localities (4941) yielded also scales of *Erythrinolepis*, as well as those of *Holcolepis*. It must be said that the Mowry shale contains scales belonging to genera also present in undoubtedly marine Benton, and *Erythrinolepis* or a very closely related form occurs in the Chico. It can not be held, consequently, that *Erythrinolepis* is a fresh-water genus. It is also out of the question to consider *Erythrinolepis* to be the scales of *Onchosaurus*, for the latter belongs to a very much later period.

The apical field of the *Erythrinolepis* scale appears in most specimens to be without any circuli, but in one good example (locality 4941, Big Horn Mountains) radiating excessively fine apical circuli can be seen, about four or five to one of the basal field. Laterally these circuli are nearly at right angles to the lateral ones, which are nearly vertical at this point. In the Erythrininae it is the apical series of circuli which is much coarser than the basal, and the lateral apical ones are continuous with the basal. We must suppose that *Erythrinolepis* represents a distinct family, Erythrinolepidae, though it can not be adequately defined.

Erythrinolepis mowriensis Cockerell, n. sp.

Plate XXXVI, figures 3–6.

Scales obtusely subtriangular, the base gently convex; radii basal, apical and lateral, very irregular, and often incomplete. The type is about 5 millimeters in diameter.

Type from U. S. G. S. locality 6713, southeast of camp at old chimney, Sisters Hill, Buffalo, Wyo., in Mowry shale. (Collected by O. B. Hopkins.) *Holcolepis transversus* is from the same locality.

Some other collections contain this species, as follows:

U. S. G. S. locality 4896. North of Wolf Creek canyon, Big Horn Mountains, Wyo. (Collected by T. E. Williard.) Accompanied by *Holcolepis* and *Leucichthyops*.

U. S. G. S. locality 4941. About 2¾ miles west of Klondike, Wyo. (Collected by T. E. Williard.) With *Holcolepis*. The *Erythrinolepis* scale figured is 7 millimeters in diameter.

These localities are all in the Mowry shale.

Erythrinolepis chicoensis Cockerell, n. sp.

Plate XXXVI, figures 1, 2.

Very similar to *E. mowriensis* but nearly circular, a little broader than long, not subtriangular. The type is 11 millimeters in diameter; another is 10 millimeters. This is a larger species than *E. mowriensis*.

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[1] Biol. Bull., vol. 20, pl. 3, fig. 18, 1911.

[2] Eastman, C. R., Dentition of *Hydrocyon* and its supposed fossil allies: Am. Mus. Nat. Hist. Bull., vol. 37, pp. 757–760, 1917.

[3] Dr. G. A. Boulenger, of the British Museum, writes me that he has read Dr. Eastman's paper and thinks his identification of *Onchosaurus* with the Characinidae highly probable. He adds: "I shall be pleased if he is right, as I predicted the discovery of Upper Cretaceous characinids in 1905 (Rept. Brit. Assoc.)." I thought it possible that *Phractolaemus* might be found to have similar teeth, but Dr. Boulenger informs me that the teeth of this genus do not show the characteristic base of *Onchosaurus* and *Hydrocyon*.

U. S. G. S. locality 7030. Cretaceous, Chico group, south side of Ortigalito Creek, Cal., in Moreno formation. (Collected by Robert Anderson.) For additional particulars see description of *Pomolobus chicoensis* (p. 180).

Family CTENOTHRISSIDAE.

The remarkable genus *Ctenothrissa*, from the Cretaceous of England and Syria, has the pelvic fins enlarged and far forward, and the type species was originally described by Pictet as a *Beryx*. Woodward pointed out the numerous differences from the berycoids and placed the fishes in a distinct family among the Isospondyli. It must be stated, however, that the scales of *C. radians* (Agassiz), which I am able to figure (Pl. XXXVII, fig. 1) through the kindness of Dr. Woodward, are extraordinarily like those of the berycoid *Hoplopteryx* (Pl. XXXVII, fig. 2), though the latter have coarser circuli. The scales also resemble those of *Myripristis* (Holocentridae), a living berycoid. The lateral circuli are vertical, not transverse, as in the clupeoids. It seems probable, therefore, that *Ctenothrissa* represents a real advance in the direction of the Percomorphi and should stand as the type of a superfamily Ctenothrissoidea, of equal rank with the Clupeoidea (Clupeoidei) and Salmonoidea (Salmonoidei). I examined the scales of *C. radians* (Agassiz) and *C. microcephala* (Agassiz) in the British Museum a number of years ago. The latter are remarkable for their width and are excellently figured by Woodward in his work on the fishes of the English chalk, Plate XVIII, figure 9. Figure 8 of the same plate, based on a scale from Reigate, Surrey, is evidently quite distinct. It is extremely broad, with about 12 basal radii arranged fanwise, and the apical margin bears long spinelike teeth. Except for the shape, this resembles the scales of the Gonorhynchidae.[1] It may be designated *Gonorhynchops* (n. gen.) *woodwardi* n. sp., and may be separated from the gonorhynchid *Charitosomus* by the shape of the scales. The latter genus, with elongate scales, is known from the Cretaceous of Westphalia and Syria. *Aulolepis* Agassiz, the other genus ascribed to the Ctenothrissidae, has totally different cycloid scales. It occurs in the Turonian of Sussex, Kent, and Surrey. The scales resemble in a general way those of the living berycoid *Plectromus lugubris* (Gilbert), from Bering Sea, but the latter lack the strong concentric lines on the exposed portion. The large lateral line canal or ridge is also suggestive of the berycoids.

Order INIOMI.

Family ENCHODONTIDAE.

Stewart recognizes a separate family, Stratodontidae, for *Stratodus* and *Cimolichthys*.

Genus HALECODON Cockerell, n. gen.

A genus of Enchodontidae related to *Halec* Agassiz is represented by the palatine and ectopterygoid, the suture being between the tenth and eleventh tooth from end in type. The palatine resembles that of *Halec* but is more slender, with the teeth, except the two apical ones, smaller. There are no long teeth like those of *Enchodus*. The ectopterygoid, compared with that of *Halec*, is much more elongated basally and bears on its apical half a great number of small teeth. The superior angle is above the basal end of the tooth row. Type *H. denticulatus*.

Halecodon denticulatus Cockerell, n. sp.

Plate XXXVI, figure 7.

Length of the combined bones about 54 millimeters, the palatine slender and pointed at end. Teeth at end of palatine about 1.7 millimeters long, sharply pointed; teeth on ectopterygoid about 1 millimeter long.

U. S. G. S. locality 3870. Cretaceous, Aspen shale, near Spring Valley, Wyo., in the SW. ¼ SW. ¼ sec. 24, T. 15 N., R. 118 W. (Collected by A. R. Schultz.) With it are various scales, including poorly preserved *Holcolepis*, probably *transversus*.

Halecodon is doubtless without scales but probably with some dermal scutes. A. S. Woodward[2] says of *Halec:* "A regular squamation of very small scales, the exposed area of each quadrangular in shape; no enlarged scutes." In a later work, however,[3] he states that no traces of scales have been observed in the species described, but enlarged dermal scutes occur on the tail. All reference to scales is omitted from the generic diagnosis, and thus *Halec* in this respect agrees with the other Enchodontidae. No doubt *Halecodon* has similar features.

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[1] Compare Am. Mus. Nat. Hist. Bull., vol. 3, pl. 4, fig. 4, 1890.

[2] Catalogue of fossil fishes in the British Museum, pt. 4, p. 212, 1901.

[3] The fossil fishes of the English chalk, p. 55, 1902.

Genus CIMOLICHTHYS Leidy.

The American forms from the Niobrara of Kansas, described under five names by Cope, are now considered to represent a single species, *C. nepaholica* (Cope). A specimen (Colorado Univ. Mus. 5388) collected by Prof. Mead in the Benton (Cretaceous) west of Laramie, Wyo., represents the top of the head and agrees excellently with this genus. The skull was a trifle smaller and somewhat narrower than that of *C. lewesiensis* Leidy, and also narrower than the American *C. nepaholica*. No doubt a distinct species is indicated, but more material is desirable. It is not certain that *Stratodus* can be distinguished from *Cimolichthys* by the parts here preserved.

Genus ENCHODUS Agassiz.

Enchodus sp.

Plate XXXVI, figure 9.

The operculum of a species of *Enchodus* was discovered in the Colorado shale of the Milk River coal field, Mont. U. S. G. S. locality 6187, in sec. 3, T. 29 N., R. 19 E., in black shale south of Miller's No. 1 ranch. (Collected by L. J. Pepperberg.) Numerous species are known from the Niobrara of Kansas.

Family TOMOGNATHIDAE.

The only known representative of the Tomognathidae, *Tomognathus mordax* Dixon, is founded on fragments from the chalk of Kent, Sussex, and Surrey. It is said to suggest affinity with the deep-sea Stomiatidae. No scales are mentioned in the description, and there presumably were none, as in the living forms supposed to be related.

Family MYCTOPHIDAE.

The family Myctophidae has been made a depositary for miscellaneous more or less obscure genera. *Ichthyotringa* Cope, from the Niobrara of South Dakota, has been referred to *Rhinellus* Agassiz, a genus of the Westphalian and Syrian Cretaceous. Hay considers the genus to belong to the Dercetidae (Heteromi), but it has been regarded as the type of a distinct family, Rhinellidae, though Dr. D. S. Jordan (in letter) doubts the validity of this course. Four species of *Sardinius* or *Leptosomus*, small fishes with (at least in two of them) cycloid scales, are described from the Niobrara of South Dakota. I can add nothing to Hay's account. *Osmeroides illustrans* (Woodward), described under *Sardinioides*, from the chalk of Kent, shows affinity with the Aulopidae.

Family NOTACANTHIDAE.

Pronotacanthus Woodward is from the Cretaceous of Mount Lebanon, Syria. No scales can be distinguished. The modern representatives of the family are described as having very small cycloid scales.

Order APODES.

Family ANGUILLAVIDAE.

Anguillavus Hay, from the Cretaceous of Mount Lebanon, retains the pelvic fins. The scales are said to be rudimentary or absent.

Family URENCHELYIDAE.

Urenchelys Woodward, from the Cretaceous of Mount Lebanon, differs from Tertiary and living eels by having a distinct caudal fin. The scales are described as "rudimentary." A species provisionally referred to the same genus occurs in the Turonian of Sussex and Kent.

Family ENCHELIIDAE.

Enchelion Hay, from Mount Lebanon, has no scales.

Order HETEROMI.

Family HALOSAURIDAE.

Genus ECHIDNOCEPHALUS Von der Marck.

Echidnocephalus? americanus Cockerell, n. sp.

Plate XXXVI, figure 10.

Scale subquadrate, longer than broad, 3 millimeters wide; nucleus subapical; apical margin not ctenoid but ragged and free from circuli (exactly as in living *Halosaurus*); circuli very distinct, the lateral ones parallel with margin; nine basal radii, very distinct, arranged fanwise; lower margin deeply crenate.

U. S. G. S. locality 5138. Brackish-water beds of Mesaverde formation, about 26 miles northeast of Rock Springs, Wyo., in sec. 15, T. 21 N., R. 103 W. (Collected by V. H. Barnett.) The character of the fish suggests marine conditions. The scale agrees excellently with the modern Halosauridae, such as *Halosaurus* and *Aldrovandia*, differing only in the more ordinary rounded nuclear area, which is elongated in the living fishes.

Echidnocephalus, from the Upper Cretaceous of Westphalia, is said to be essentially identical with *Halosaurus*, so I refer the scale provisionally to that genus.

Echidnocephalus? pacificus Cockerell, n. sp.

Plate XXXVI, figure 11.

Scale 6 millimeters wide, cycloid, subquadrate, rounded apically; sides rather convex; laterobasal corners very obtuse, not salient; nucleus just below the apex; six basal radii, rather widely spaced, arranged fanwise; basal margin shallowly crenate. This is more like *Halosaurus*, whereas *E.? americanus* is like *Aldrovandia*, the very apical nucleus and absence of deep basal crenation being *Halosaurus* characters.

The extremely apical nucleus also occurs in *Bathysaurus agassizi*, which, however, has subcircular scales without a trace of radii.

U. S. G. S. locality 7027. Cretaceous, Chico group, foothills between Little Panoche and Ortigalito creeks, Cal., in first canyon south of Laguna Seca Creek, in limy layer between lower gray sandstone and fossiliferous grit bed in upper part of Moreno formation. (Collected by Robert Anderson.)

Family DERCETIDAE.

A. S. Woodward says of the Dercetidae: "Ordinary scales small or wanting, but two or more continuous paired series of enlarged scutes along flanks; no median dorsal or ventral scutes." The scales are more or less triangular, the outline resembling that of shark teeth (*Isurus*). The type of *Dercetis* is *D. scutalus* Agassiz, from the Cretaceous of Westphalia. According to Woodward these fishes are apparently allied to the Halosauridae and Notacanthidae. If so, they should be placed in the order Heteromi. *Leptotrachelus longipinnis* Cope, referred to the Dercetidae, occurs in the Niobrara of South Dakota. *Triaenaspis virgulatus* Cope, also from the Niobrara of South Dakota, is referred by Woodward to *Leptotrachelus*, but Hay states that the genus *Triaenaspis* is valid. *Leptotrachelus* also occurs in the Upper Cretaceous of England, Westphalia, and Syria. Boulenger refers the Dercetidae to the Heteromi.

Order HAPLOMI.

Family CROSSOGNATHIDAE.

Crossognathus Pictet, from the Neocomian of Switzerland and Hanover, is said to have the scales large, very deeply overlapping, smooth, and not serrated or crenulated on posterior margin; a simple tube pierces the lateral line scales. *Syllaemus* Cope was formerly referred to this family, but Woodward now considers it a primitive clupeoid. It has not the transverse circuli of the scales of Clupeidae.

Apsopelix and *Pelecorapis* of Cope have been listed under Crossognathidae; Hay placed the first doubtfully in Albulidae, the second in Mugillidae.

Apsopelix sauriformis Cope came from Bunker Hill station on the Union Pacific Railroad of Kansas. Mr. T. W. Stanton tells me that this is certainly in the Benton. Cope says that the scales are "large and cycloid. They do not present a trace of radii but are marked with fine and close concentric grooves [circuli]; these assume a vertical direction on the exposed surface, and are there more irregular, the more marginal ones terminating above and below. But few (i. e., the central) grooves are truly circular."

Order SYNENTOGNATHI.

Family HEMIRAMPHIDAE.

Genus HEMILAMPRONITES Steinla.

The generic name *Hemilampronites* was published by Geinitz from Steinla's manuscript for certain scales found in the Turonian of Saxony. The species was called *H. steinlai* Geinitz. As a matter of fact the scales agree well enough with *Hyporhamphus* and would be referred to that genus without question were they not from the Cretaceous.

Hemilampronites hesperius Cockerell, n. sp.

Plate XXXVI, figure 13.

Scale 12 millimeters in diameter, broader than long, cycloid, without radii (*Hyporhamphus* has a few); circuli of apical field extremely fine and regular, extending across scale; the other circuli much coarser and widely spaced at sides, where they pass transversely and more or less obliquely (especially above) to the margin, the upper nearly at right angles with the fine circuli of the apical field.

Differs from *H. steinlai* by the absence of basal radii and the oblique upper lateral circuli.

U.S.G.S. locality 9190. Cretaceous, Fox Hills sandstone, Greeley quadrangle, Colo., in second large ravine 2¼ miles south of Milliken and half a mile west of railroad track near Wildcat Mound, in sec. 23, T. 4 N., R. 67 W. (Collected by T. E. Williard.)

A related fish (*Hemiramphus edwardsi* Bassani) has been found in the upper Eocene near Verona. Regan suggests that *Cobitopsis* from the lower Oligocene of France, referred by Woodward to the Ammodytidae, may belong to the same group as the fishes now discussed, in the immediate vicinity of *Chriodorus*, if indeed distinct from that genus. No scales were found on the fossil *Cobitopsis*. Ammodytid scales[1] are very unlike those of the Hemiramphidae.

Order PERCOMORPHI.

Suborder BERYCOIDEI.

Family PLATYCORMIDAE Jordan (in letter).

Platycormus Von der Marck, from the Cretaceous of Westphalia, is described by Woodward as having the scales ctenoid, of moderate size, more or less ornamented with granulations, and extending over the opercular apparatus, head, and base of median fins. There are no enlarged or thickened scales. This genus, along with *Omosoma* Costa, from Mount Lebanon, and *Berycopsis* Dixon, has been provisionally regarded as belonging to the Stromateidae. It is also to be noted that the Cretaceous scales figured by Geinitz in the work already cited (especially his fig. 3; fig. 4 may be latinucleate) as *Aspidolepis steinlai* agree with those of the Stromateidae (*Poronotus*).

Family BERYCOPSIDAE Jordan (in letter).

Berycopsis Dixon is represented by three species in the English chalk. At the British Museum I examined the large broad scales of *B. major* Woodward, from the Middle Chalk of Cuxton, Kent. They are about 25 millimeters broad, with fine grooving toward the apex; they are not strictly ctenoid. These scales are extremely like those of *Hoplopteryx lewesiensis*. *Berycopsis elegans* Dixon, the type of the genus, has much smaller scales, and it seemed to me hardly possible that it could be congeneric with *B. major*. Woodward states, however, that the structural characters of the two are about the same. *B. pulchellus* (Dixon) is allied to *B. major*.

Family HOPLOPTERYGIDAE Cockerell, n. fam.

Based on *Hoplopteryx* Agassiz. Resembling the Trachichthyidae, but anal spines four, as in Berycidae; scales as in Holocentridae. Dorsal fin without the notch or division of the Holocentridae, and its spines much fewer (six). Anal fin very much shorter than in *Beryx*, but dorsal longer. Although the scales of *Hoplopteryx* resemble those of *Berycopsis*, the fish is very different in a number of characters and can not be very closely related. Both anal and dorsal fins of *Berycopsis* are extremely long. *Beryx insculptus* Cope, from the Cretaceous of New Jersey, is very imperfectly known, but the scales agree with *Hoplopteryx* and not with *Beryx*. It may be provisionally called *Hoplopteryx? insculptus*.

The berycoid fishes were certainly well developed in Cretaceous time, and to-day we seem to have only remnants of a once more numerous group. The modern families, for scales of which I am indebted to Dr. D. S. Jordan, the United States National Museum, the United States Bureau of Fisheries, and the Museum of Comparative Zoology, have the following scale characters:

Polymixiidae: *Polymixia japonica* Steindachner has very broad scales, with strongly crenulated lower margin, and the apical margin strongly, irregularly dentate. It differs from the Holocentridae at once in the broad fanlike basal undulations rather than distinct radii, though it is approached in this by *Ostichthys*. It differs from *Ostichthys* by the much smaller, irregular teeth, and radically in the widely spaced circuli, the lateral ones oblique and entering the margin. In *Ostichthys* the circuli are excessively fine (though the scale is much larger), and the lateral ones are vertical. I know of no Cretaceous scale like that of *Polymixia*.

Holocentridae: The holocentrid scale seems to be the ancient one of the group, to judge from the fossils, though the fins of the modern family are much modified. The very strong, widely spaced apical keels terminating in teeth, so well shown in the scale figured by Geinitz and quite wrongly atrtibuted to *Macropoma mantelli*, appear (even more widely spaced) in the living *Ostichthys pillwaxi*, from the Hawaiian Islands (Pl. XXXVI, fig. 8). *Myripristis* scales differ from those of *Ostichthys* by the much closer teeth, about three to one. *Flammeo* scales are not nearly as broad as those of the genera just mentioned, and the basal margin has a distinct median prominence, sometimes broken up into several little ones in *F. scythrops*. *Holocentrus* scales are broad, usually with several radii close together in the middle of the base.[1] The apical teeth are like those of a coarse comb, not keeled as in *Ostichthys* and the Geinitz scale.

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[1] See Gill, Theodore, U. S. Nat. Mus. Proc., vol. 28, p. 162, 1904.

Berycidae: Scales of *Beryx splendens* Lowe are cycloid, with the broad hyaline marginal area beset with small tubercles or spines. In other species, as *B. lineatus*, the marginal area is beset with long spines, the most apical projecting beyond the margin. Basal radii are feeble or absent. The structure of the apical field is thus different in the Berycidae from that of the Holocentridae. In the former there are spines scattered over a surface, in the latter strong ridges or apical teeth. The true berycid type apparently does not appear among the Cretaceous fossils.

Trachichthyidae: *Trachichthys australis* has the broad and very dense scales constructed after the type of the Berycidae, the apical field being densely spinose. Dr. Jordan kindly sends me scales of two other genera, which he formerly placed with the Berycidae but has more recently referred to the Trachichthyidae. They are utterly diverse from each other and from the other berycoids here discussed. *Plectromus lugubris* (Gilbert), from the vicinity of Bogoslof Island, Bering Sea, has subquadrate cycloid scales, with widely spaced circuli, and three or four basal radii arranged fanwise. *Caulolepis longidens*, from deep water off Hawaii, has very small roundish scales, with four or five very widely spaced spinelike marginal projections.

Monocentridae: *Monocentris japonicus* has the scales with a high central keel or crest, but otherwise it is of the *Trachichthys* type, with spinose apical field.

We must evidently consider that the modern berycoids are variously specialized descendants of the Cretaceous forms, none of them retaining the same combinations of characters. The precise arrangement of the Cretaceous genera for the present remains uncertain. Woodward figures the scales of the English Cretaceous *Homonotus* Dixon and *Trachichthyoides* Woodward. Both have scales of the holocentrid type, not of the berycid-trachichthyid type. The opercular apparatus of *Trachichthyoides* readily separates it from *Hoplopteryx*. Some of the genera, as *Dinopteryx* Woodward, from Mount Lebanon, have cycloid scales.

The total absence of berycoids from the interior region of the United States has seemed remarkable. The Cretaceous scales from the Rocky Mountain region that I have examined do not include any undoubted berycoids, though a few poorly preserved specimens, which I have not ventured to describe, might conceivably be aberrant berycoids. Cope's genus *Pelecorapis* is of uncertain affinities. The scales of *P. berycinus* Cope, as figured by him, closely resemble those of *Hoplopteryx? insculptus* (Cope). The type of the genus is, however, *P. varius* Cope, found in Kansas, almost certainly in the Benton. It is said to have abdominal ventral fins, and to be related in a general way to the Scombresocidae, Atherinidae, etc. It can not well belong to the berycoids, nor does Cope's account of the scales suggest such a reference. The second species, *P. berycinus*, is of very doubtful generic position. It is equally uncertain as to locality and age, and may very well not be from Montana, as Mr. Stanton informs me. We are thus still left without berycoids in the Cretaceous mediterranean sea of America.

Order ACANTHOPTERI.

It is possible that the Stromateidae existed in Cretaceous time. The scale of *Aspidolepis steinlai* Geinitz, from the Turonian of Saxony, certainly resembles that of the living *Poronotus*. It is cycloid, with the lateral circuli more or less angled. *Omosoma* Costa, from Mount Lebanon, has been provisionally referred here. Woodward describes the scales as small, smooth, and cycloid, apparently longer than deep, extending over the opercular apparatus, head, and base of anal and dorsal fins. Woodward[2] remarks that the Cretaceous fishes which he provisionally assigned to the Stromateidae are primitive scombroids of uncertain affinities. It must be said that the stromateid scale of to-day is very similar to that of the scombroids, and it is thus easy to suppose that the Cretaceous fishes were rather of the latter than the former group.

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[1] See U. S. Bur. Fisheries Bull. for 1912, pl. 36, fig. 26.

[2] The fossil fishes of the English chalk, p. 5, 1902.

Carangidae are recorded from the Cretaceous of Europe and Syria, the principal genus being *Aipichthys* Steindachner, with small, thin, cycloid scales and a series of ventral ridge scales on the short abdominal region before the dorsal fin. *Bathysoma lutkeni* Davis, from the Danian of Scandinavia, said by Woodward[1] to be "very curiously specialized."

Prolates Priem, with "scales small and very finely serrated," is from the Upper Cretaceous of France and has been referred to the Percidae. So far as I know, the typical percoid scale does not appear in the Cretaceous, but is first found near the base of the Tertiary, in a fresh-water deposit, as described below.

Family CENTRARCHIDAE.

Genus CENTRARCHITES Cockerell, n. gen.

Fresh-water fishes with scales agreeing with Centrarchidae or Micropteridae but not definitely assignable to a known genus. Type *C. coloradensis.*

Centrarchites coloradensis Cockerell, n. sp.

Plate XXXVI, figure 12.

Scale subquadrate, transverse diameter 9 millimeters; apical margin not distinctly dentate, but apical field with a broadly triangular *ctenoid* patch, as in the young of *Ambloplites;* nucleus far apical of middle, just below lower end of ctenoid patch, the surrounding circuli transversely oval (more so than in modern genus); basal radii occupying about middle third (transversely) of scale, about nine, close together, with very fine transverse circuli between; lateral circuli parallel with margin.

U. S. G. S. locality 7087. Eocene, Coalmont formation, about 1 mile southwest of Walden, Colo. (Collected by A. L. Beekly.) This is Beekly's locality 1.[2] With it is a fragment of a *Viviparus* and a fragment of a *Laurus*-like leaf. There is also another species of fish scale, nearly circular, with very fine circuli, possibly salmonoid.

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[1] The fossil fishes of the English chalk, p. 253, 1912.

[2] U. S. Geol. Survey Bull. 596, p. 63, 1915.

PLATE XXXI.

PLATE XXXI.

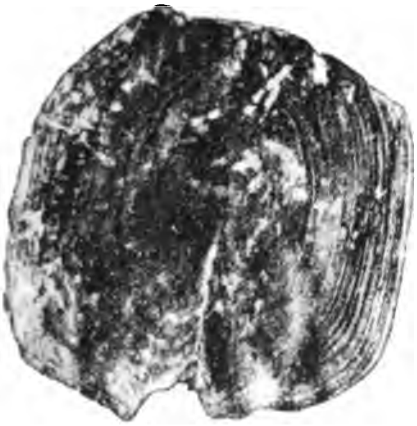
FIGURE 1. *Petalolepis? fibrillatus* Cockerell (p. 172). Type, × 6. U. S. G. S. locality 5094. U. S. N. M. catalogue No. 8662.

2. *Cycloides? incertus* Cockerell (p. 173). Type, × 3. U. S. G. S. locality 5177. U. S. N. M. catalogue No. 8663.

3, 4. *Holcolepis pulchellus* Cockerell (p. 174):
    3. Type, × 8. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8664.
    4. Another specimen, × 6. U. S. G. S. locality 7108. U. S. N. M. catalogue No. 8665.

5. *Holcolepis delicatus* Cockerell (p. 175). Type, × 4. U. S. G. S. locality 8916. U. S. N. M. catalogue No. 8666.

6–13. *Holcolepis transversus* Cockerell (p. 175):
    6. Type, × 4. U. S. G. S. locality 6682. U. S. N. M. catalogue No. 8667.
    7. × 3. U. S. G. S. locality 6681. U. S. N. M. catalogue No. 8668.
    8. × 3. U. S. G. S. locality 6713. U. S. N. M. catalogue No. 8669.
    9. × 4. U. S. G. S. locality 6682. U. S. N. M. catalogue No. 8670.
    10. × 4. U. S. G. S. locality 6713. U. S. N. M. catalogue No. 8671.
    11. × 4. U. S. G. S. locality 3417. U. S. N. M. catalogue No. 8672.
    12. × 4. U. S. G. S. locality 6682. U. S. N. M. catalogue No. 8673.
    13. × 3. U. S. G. S. locality 4421. U. S. N. M. catalogue No. 8674.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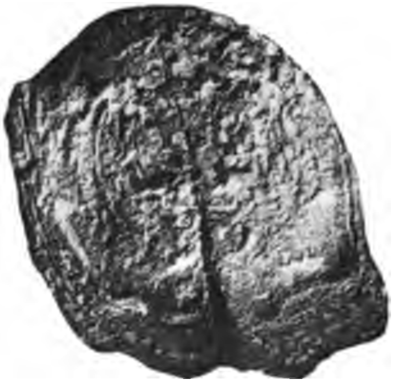
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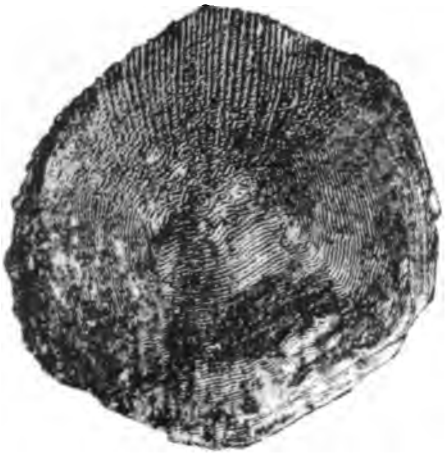
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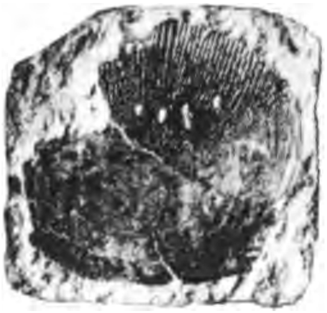
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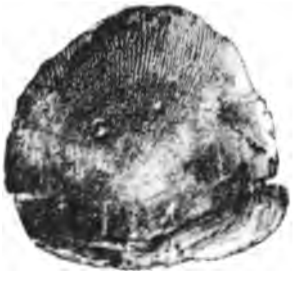
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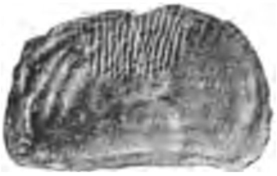
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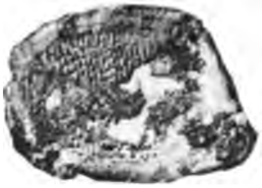
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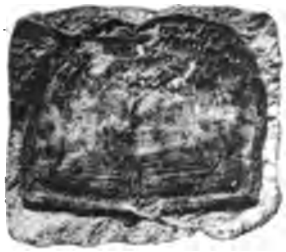
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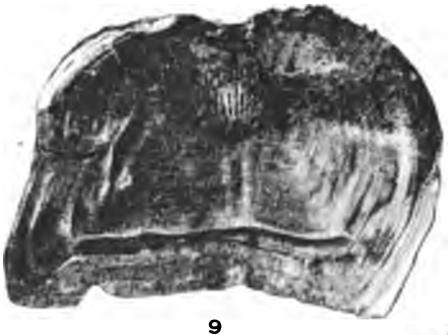
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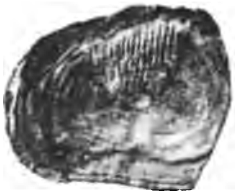
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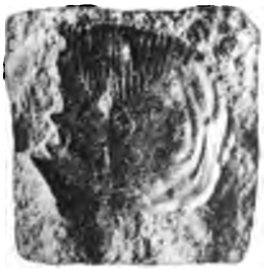
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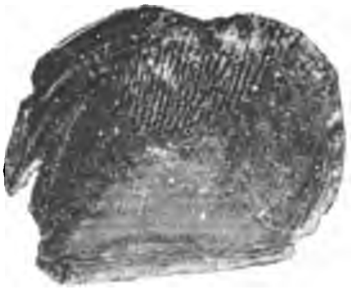
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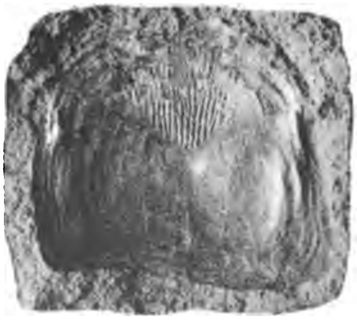
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CRETACEOUS FISH SCALES

PLATE XXXIV.

FIGURE 1. *Chicolepis punctatus* Cockerell (p. 177). Type, × 3. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8682.

2. *Hypsodon lowii* (Stewart) Cockerell (p. 178). Scale, × 2. U. S. G. S. locality 7294. U. S. N. M. catalogue No. 8683.

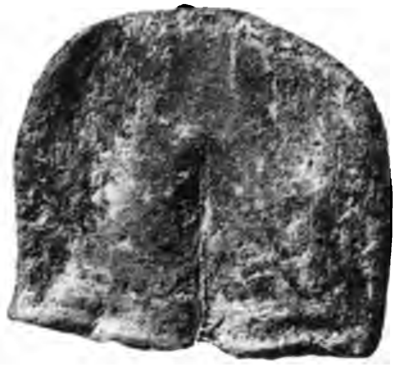
3. *Ichthyodectes* sp. (p. 179). Lateral line scale, × 4. U. S. G. S. locality 2402. U. S. N. M. catalogue No. 8684.

4. *Ichthyodectes* sp. (p. 179). Lateral line scale, × 4. U. S. G. S. locality 7277. U. S. N. M. catalogue No. 8685.

5. *Pomolobus? chicoensis* Cockerell (p. 180). Type, × 10. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8686.

6–12. Cretaceous fish scales from Turkestan (p. 179). Copied from G. D. Romanowsky, Materialui dlya geologii Turkestanskago kraya, pts. 2, 3, 1884, 1890.
  - 6–8. *Hypsodon* sp. Figured as *Cladocyclus strehlensis* Geinitz. Op. cit., pt. 3, pl. 17, figs. 6a–c.
  - 9. *Hypsodon?* sp. Figured as *Osmeroides lewesiensis* (variety). Idem, pt. 2, pl. 23, fig. 4a.
  - 10. *Ichthyodectes* sp. Figured as *Cladocyclus strehlensis.* Idem, pt. 2, pl. 23, fig. 4b.
  - 11. *Ichthyodectes? pectinolepis.* Figured as *Osmeroides pectinolepis* Romanowsky. Idem, pt. 3, pl. 17, fig. 5.
  - 12. Undetermined scale. Figured as *Beryx* sp. Idem, pt. 3, pl. 17, fig. 4.

13. Fragment of Mowry shale, × 2, showing scales of *Erythrinolepis mowriensis*, *Leucichthyops vagans*, and *Holcolepis transversus* (pp. 182, 180, 175). U. S. G. S. locality 4896, north of Wolf Creek canyon, Big Horn Mountains, Wyo. U. S. N. M. catalogue No. 8687.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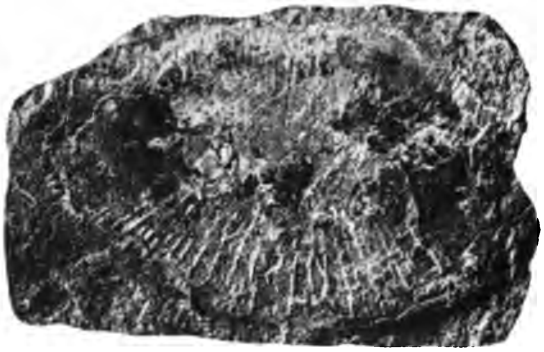
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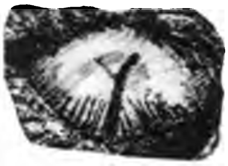
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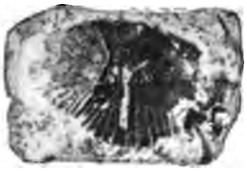
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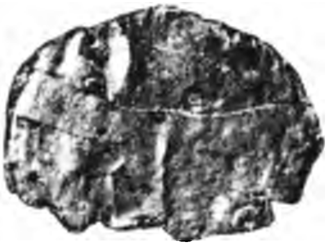
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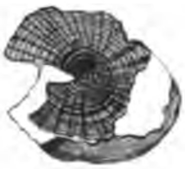
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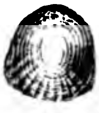
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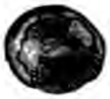
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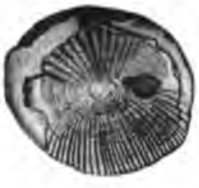
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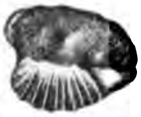
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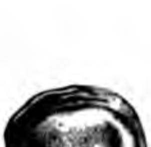
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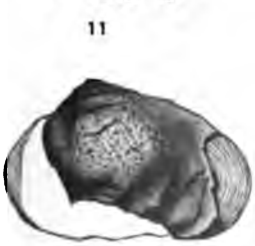
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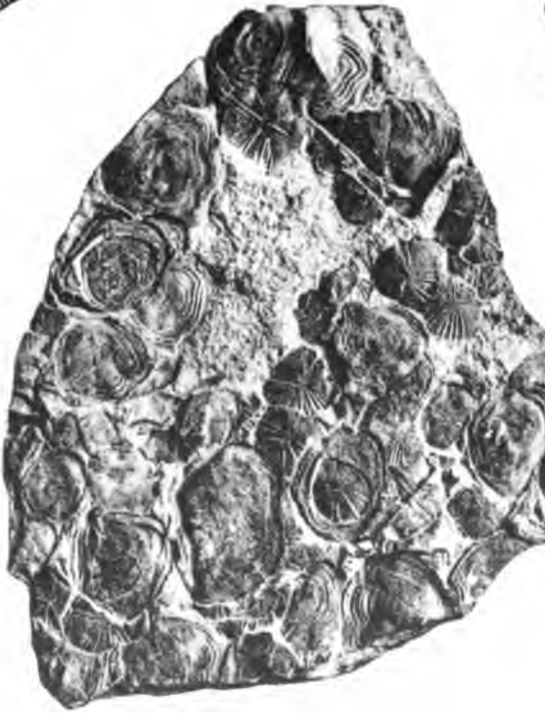
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CRETACEOUS FISH SCALES

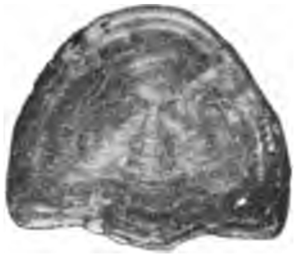
PLATE XXXV.

PLATE XXXV.

FIGURES 1-15. *Leucichthyops vagans* Cockerell (p. 180):

1. Type, × 4. U. S. G. S. locality 7095. U. S. N. M. catalogue No. 8688.
2, 3. Two scales, × 3. Carbon County, Wyo. U. S. N. M. catalogue Nos. 8689, 8690.
4. Scale, × 4. Black Hills, S. Dak. U. S. N. M. catalogue No. 8691.
5. Scale, × 3. U. S. G. S. locality 3880. U. S. N. M. catalogue No. 8692.
6. Scale, × 3. U. S. G. S. locality 7275. U. S. N. M. catalogue No. 8693.
7. Narrow scale, × 3. U. S. G. S. locality 6681. U. S. N. M. catalogue No. 8694.
8. Scale, × 4. U. S. G. S. locality 8916. U. S. N. M. catalogue No. 8695.
9. Narrow scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8696.
10. Lateral line scale, × 4. U. S. G. S. locality 6682. U. S. N. M. catalogue No. 8697.
11. Lateral line scale, × 4. U. S. G. S. locality 7095. U. S. N. M. catalogue No. 8698.
12. Lateral line scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8699.
13. Lateral line scale, × 4. U. S. G. S. locality 7100. U. S. N. M. catalogue No. 8700.
14. Lateral line scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8701.
15. Latinucleate scale, × 4. Black Hills, S. Dak. U. S. N. M. catalogue No. 8702.

16. *Cyclolepis stenodinus* Cockerell (p. 181). Type, × 4. U. S. G. S. locality 9190. U. S. N. M. catalogue No. 8703.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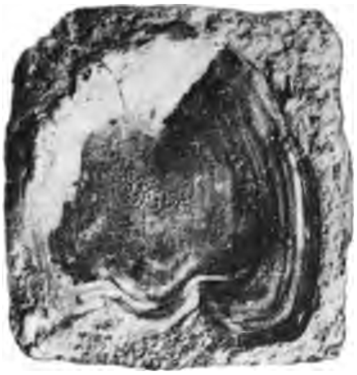
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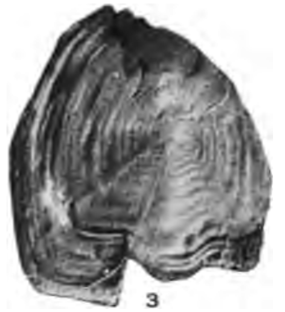
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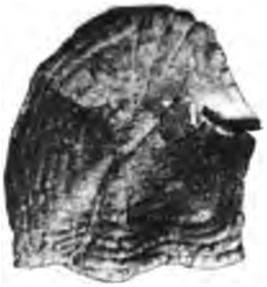
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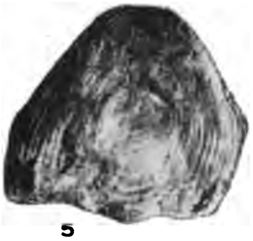
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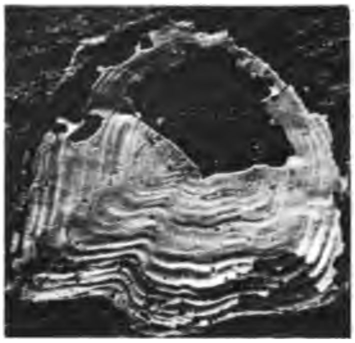
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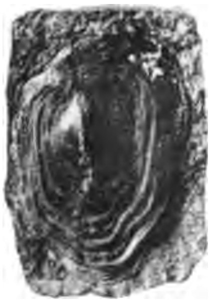
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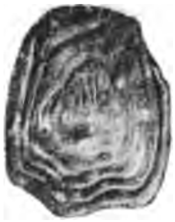
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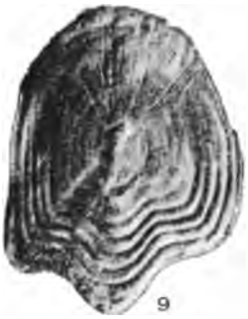
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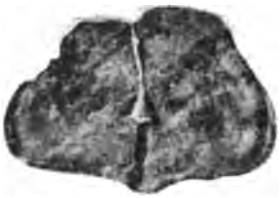
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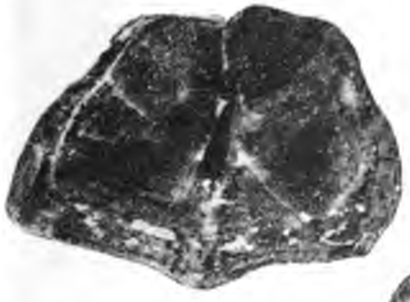
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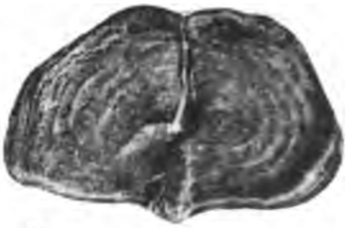
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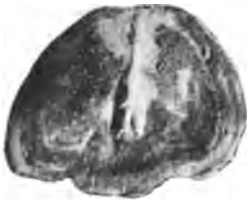
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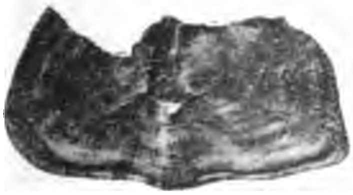
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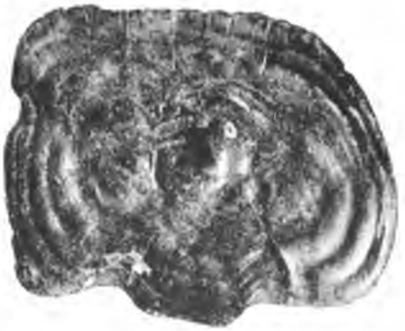
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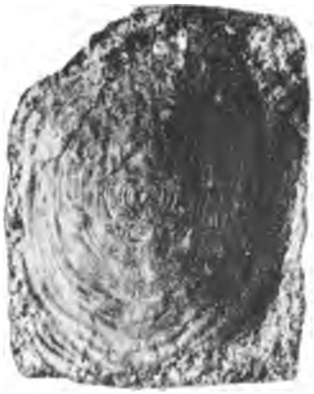
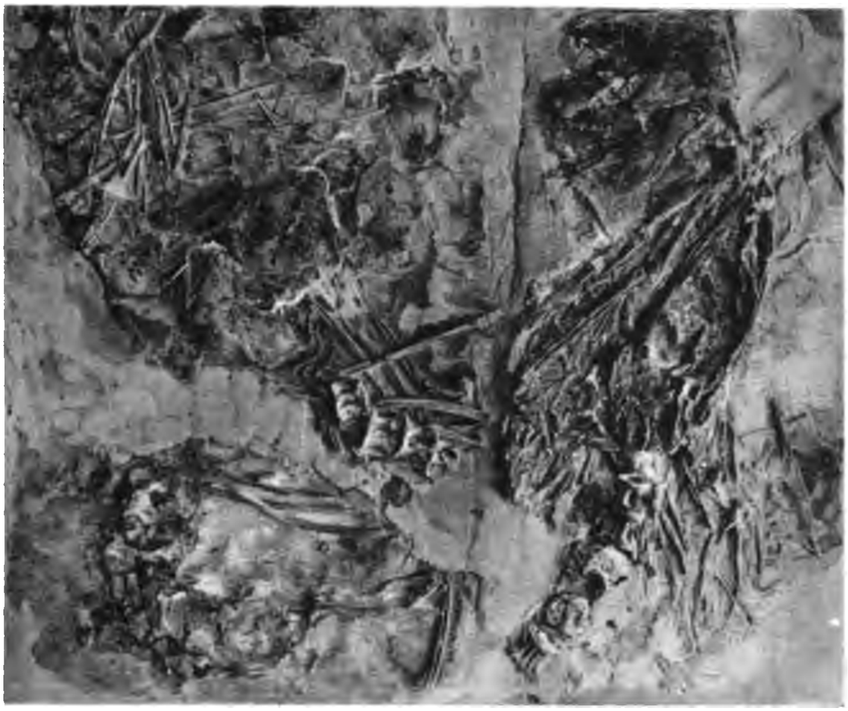

16

CRETACEOUS FISH SCALES

PLATE XXXIII.

FIGURES 1, 2. *Hypsodon audax* (Leidy) (p. 177):

1. **Specimen showing several scales and parts of skeleton. University of Kansas collection.**
2. **Part of same specimen, more enlarged.**



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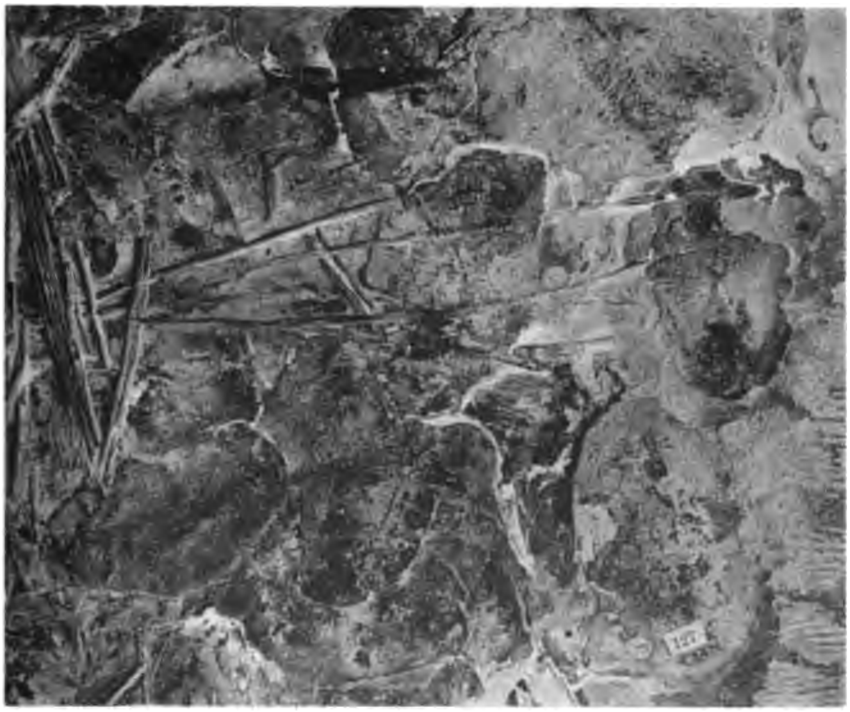


2

CRETACEOUS FISH SCALES

PLATE XXXIV.

PLATE XXXIV.

FIGURE 1. *Chicolepis punctatus* Cockerell (p. 177). Type, × 3. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8682.

2. *Hypsodon lowii* (Stewart) Cockerell (p. 178). Scale, × 2. U. S. G. S. locality 7294. U. S. N. M. catalogue No. 8683.

3. *Ichthyodectes* sp. (p. 179). Lateral line scale, × 4. U. S. G. S. locality 2402. U. S. N. M. catalogue No. 8684.

4. *Ichthyodectes* sp. (p. 179). Lateral line scale, × 4. U. S. G. S. locality 7277. U. S. N. M. catalogue No. 8685.

5. *Pomolobus? chicoensis* Cockerell (p. 180). Type, × 10. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8686.

6–12. Cretaceous fish scales from Turkestan (p. 179). Copied from G. D. Romanowsky, Materialui dlya geologii Turkestanskago kraya, pts. 2, 3, 1884, 1890.

  6–8. *Hypsodon* sp. Figured as *Cladocyclus strehlensis* Geinitz. Op. cit., pt. 3, pl. 17, figs. 6a–c.

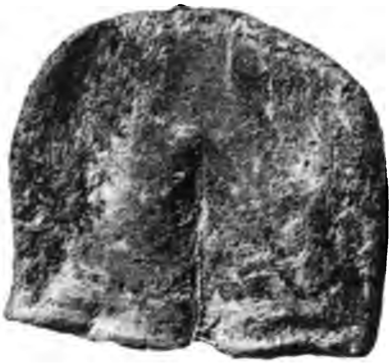
  9. *Hypsodon?* sp. Figured as *Osmeroides lewesiensis* (variety). Idem, pt. 2, pl. 23, fig. 4a.

  10. *Ichthyodectes* sp. Figured as *Cladocyclus strehlensis*. Idem, pt. 2, pl. 23, fig. 4b.

  11. *Ichthyodectes? pectinolepis*. Figured as *Osmeroides pectinolepis* Romanowsky. Idem, pt. 3, pl. 17, fig. 5.

  12. Undetermined scale. Figured as *Beryx* sp. Idem, pt. 3, pl. 17, fig. 4.

13. Fragment of Mowry shale, × 2, showing scales of *Erythrinolepis mowriensis*, *Leucichthyops vagans*, and *Holcolepis transversus* (pp. 182, 180, 175). U. S. G. S. locality 4896, north of Wolf Creek canyon, Big Horn Mountains, Wyo. U. S. N. M. catalogue No. 8687.



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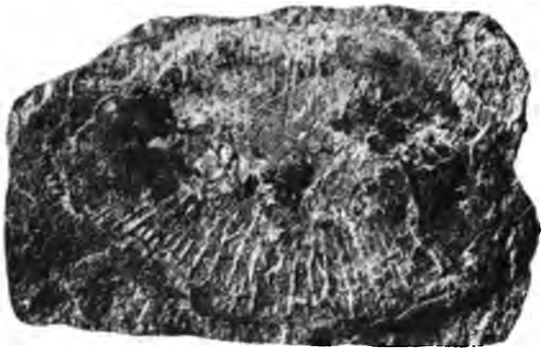

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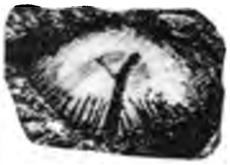

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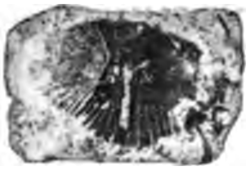

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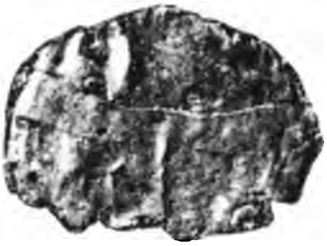

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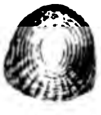

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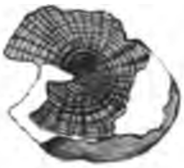

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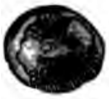

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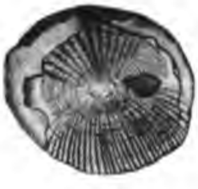

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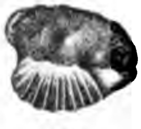

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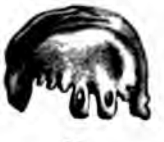

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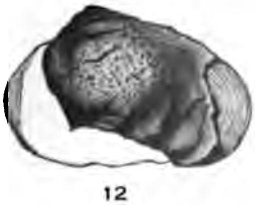

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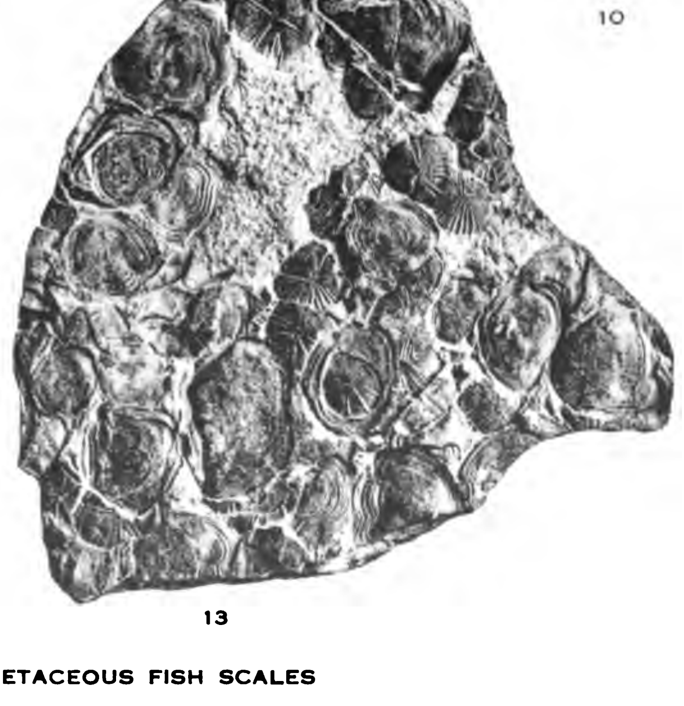

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CRETACEOUS FISH SCALES

PLATE XXXV.

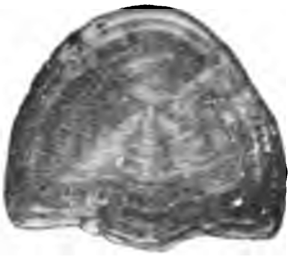
PLATE XXXV.

FIGURES 1–15. ***Leucichthyops vagans*** Cockerell (p. 180):

1. Type, × 4. U. S. G. S. locality 7095. U. S. N. M. catalogue No. 8688.

2, 3. Two scales, × 3. Carbon County, Wyo. U. S. N. M. catalogue Nos. 8689, 8690.

4. Scale, × 4. Black Hills, S. Dak. U. S. N. M. catalogue No. 8691.
5. Scale, × 3. U. S. G. S. locality 3880. U. S. N. M. catalogue No. 8692.
6. Scale, × 3. U. S. G. S. locality 7275. U. S. N. M. catalogue No. 8693.
7. Narrow scale, × 3. U. S. G. S. locality 6681. U. S. N. M. catalogue No. 8694.
8. Scale, × 4. U. S. G. S. locality 8916. U. S. N. M. catalogue No. 8695.
9. Narrow scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8696.
10. Lateral line scale, × 4. U. S. G. S. locality 6682. U. S. N. M. catalogue No. 8697.
11. Lateral line scale, × 4. U. S. G. S. locality 7095. U. S. N. M. catalogue No. 8698.
12. Lateral line scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8699.
13. Lateral line scale, × 4. U. S. G. S. locality 7100. U. S. N. M. catalogue No. 8700.
14. Lateral line scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8701.
15. Latinucleate scale, × 4. Black Hills, S. Dak. U. S. N. M. catalogue No. 8702.
16. ***Cyclolepis stenodinus*** Cockerell (p. 181). Type, × 4. U. S. G. S. locality 9190. U. S. N. M. catalogue No. 8703.



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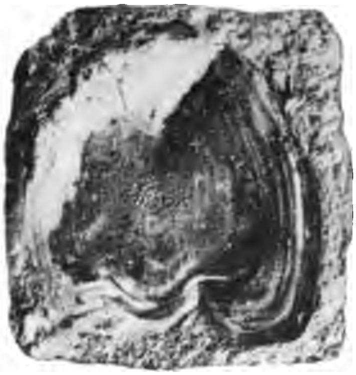

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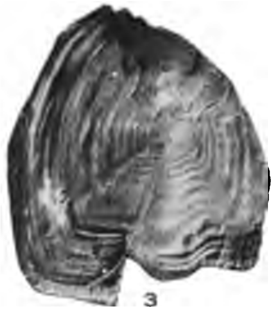

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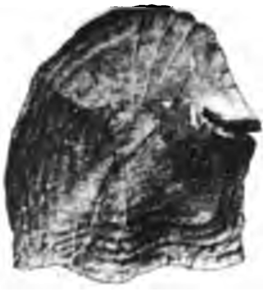

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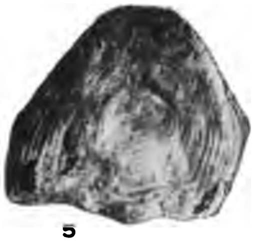

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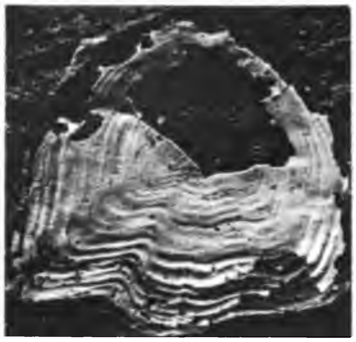

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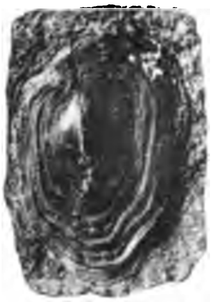

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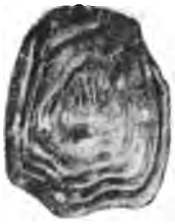

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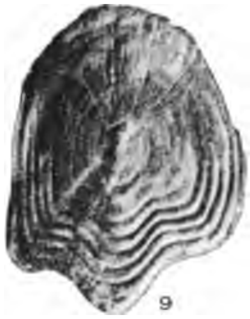

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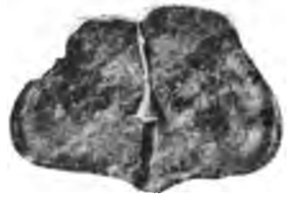

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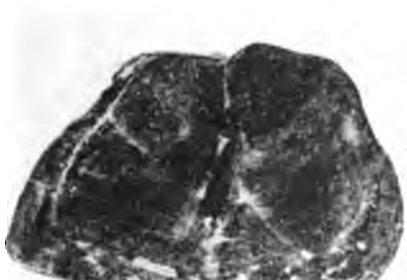

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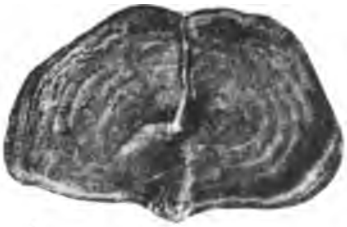

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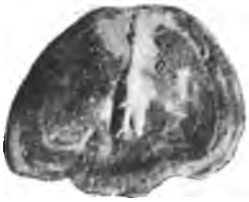

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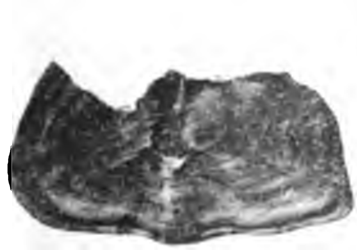

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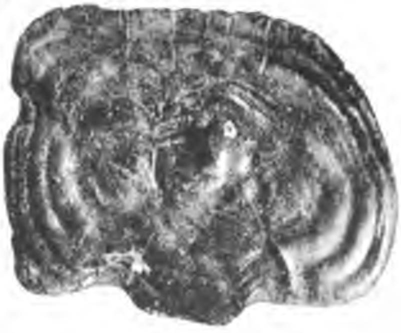

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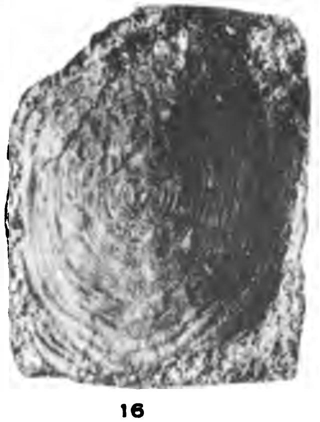


16

CRETACEOUS FISH SCALES

PLATE XXXVI.

PLATE XXXVI.

PLATE XXXVI.

FIGURES 1, 2. *Erythrinolepis chicoensis* Cockerell (p. 182):
  1. Type, × 4. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8704.
  2. Smaller scale, × 4. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8705.

3–6. *Erythrinolepis mowriensis* Cockerell (p. 182):
  3. Type, × 4. U. S. G. S. locality 6713.
  4. Scale, × 4. U. S. G. S. locality 6713.
  5. Scale, × 4. U. S. G. S. locality 6713. 3–5, U. S. N. M. catalogue No. 8706.
  6. Scale, × 4. U. S. G. S. locality 4941. U. S. N. M. catalogue No. 8707.

7. *Halecodon denticulatus* Cockerell (p. 183). Type. Palatine and ectopterygoid, × 1.5. U. S. G. S. locality 3870. U. S. N. M. catalogue No. 8708.

8. *Ostichthys pillwaxi* (p. 187). Apical region of scale, × 1.85. Honolulu market.

9. *Enchodus* sp. (p. 184). Operculum, × 2. U. S. G. S. locality 6187. U. S. N. M. catalogue No. 8709.

10. *Echidnocephalus? americanus* Cockerell (p. 184). Type, × 8. U. S. G. S. locality 5138. U. S. N. M. catalogue No. 8710.

11. *Echidnocephalus? pacificus* Cockerell (p. 185). Type, × 4. U. S. G. S. locality 7027. U. S. N. M. catalogue No. 8711.

12. *Centrarchites coloradensis* Cockerell (p. 188). Type, × 4. Eocene. U. S. G. S. locality 7087. U. S. N. M. catalogue No. 8712.

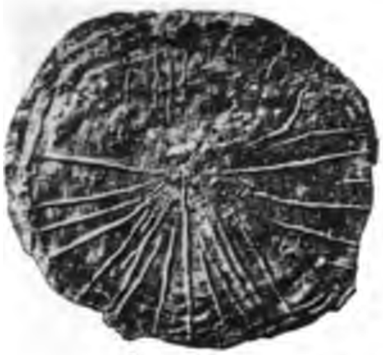
13. *Hemilampronites hesperius* Cockerell (p. 185). Type, × 6. U. S. G. S. locality 9190. U. S. N. M. catalogue No. 8713.

14. Latinucleate (regenerated) scale of undescribed species, with marginal teeth resembling those of the berycoids, × 3. U. S. G. S. locality 4867. Cretaceous, Mowry shale, sec. 1, T. 26 N., R. 88 W., near North Rawlins, Wyo. U. S. N. M. catalogue No. 8714.

15. Scale of undescribed species with marginal teeth suggesting the berycoids, × 10. U. S. G. S. locality 4426. Cretaceous, Mowry shale, SE. ¼ sec. 27, T. 33 N., R. 74 W., about 5 miles southwest of Careyhurst, Wyo. U. S. N. M. catalogue No. 8715.

16. Scale of undescribed species, × 10. U. S. G. S. locality 6603, SE. ¼ sec. 18, T. 1 S., R. 10 W., Uinta special base line, Utah. Said to be Mowry shale. The collection contains plant remains and may be from a fresh-water deposit. U. S. N. M. catalogue No. 8716.

17. Scale of undescribed species, perhaps clupeid, with fine transverse circuli, × 4. Transverse diameter 12.5 millimeters. From the same station as figure 16. Presumably fresh water. U. S. N. M. catalogue No. 8717.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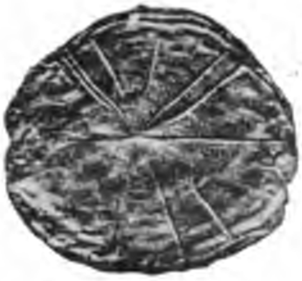
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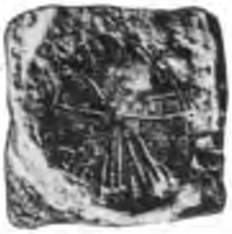
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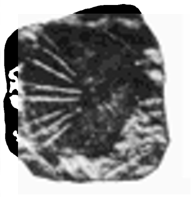
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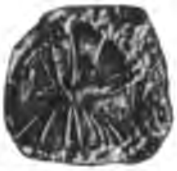
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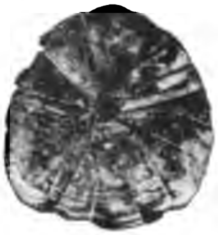
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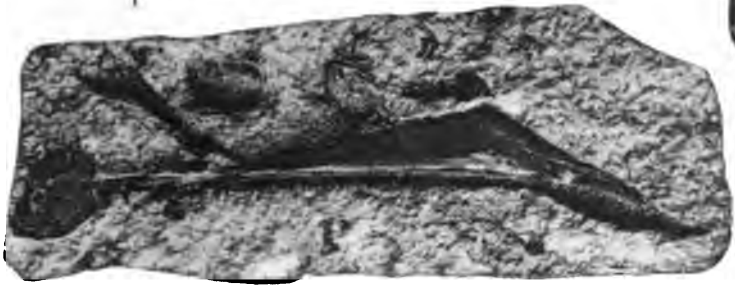
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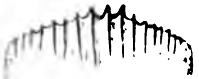
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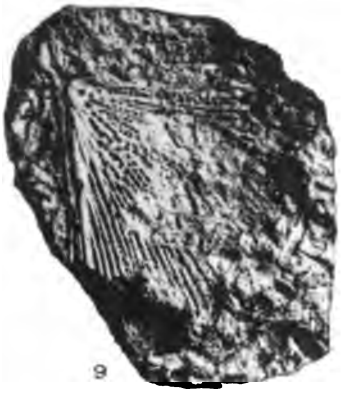
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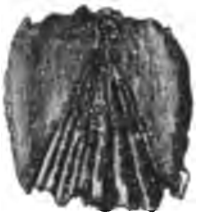
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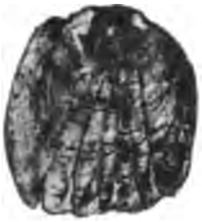
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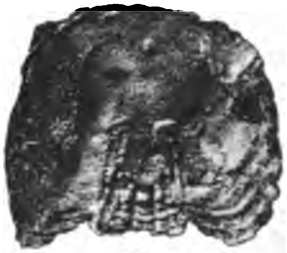
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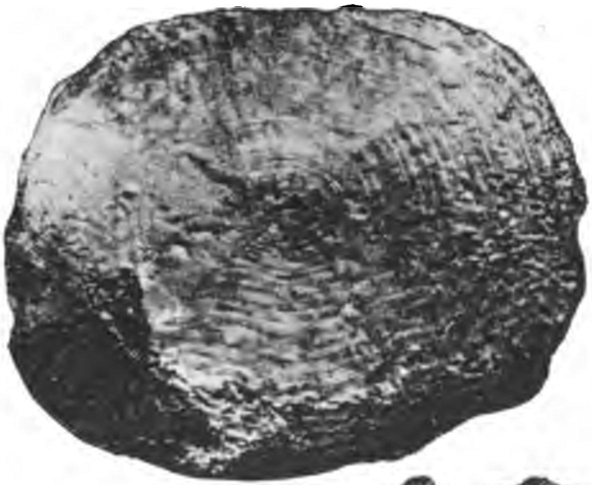
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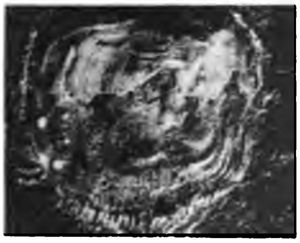
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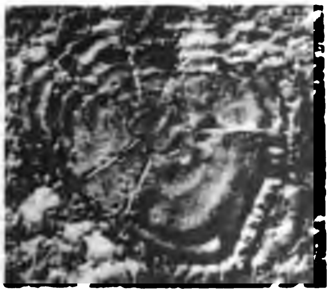
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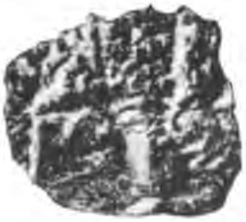
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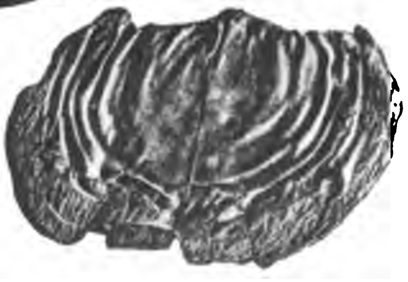
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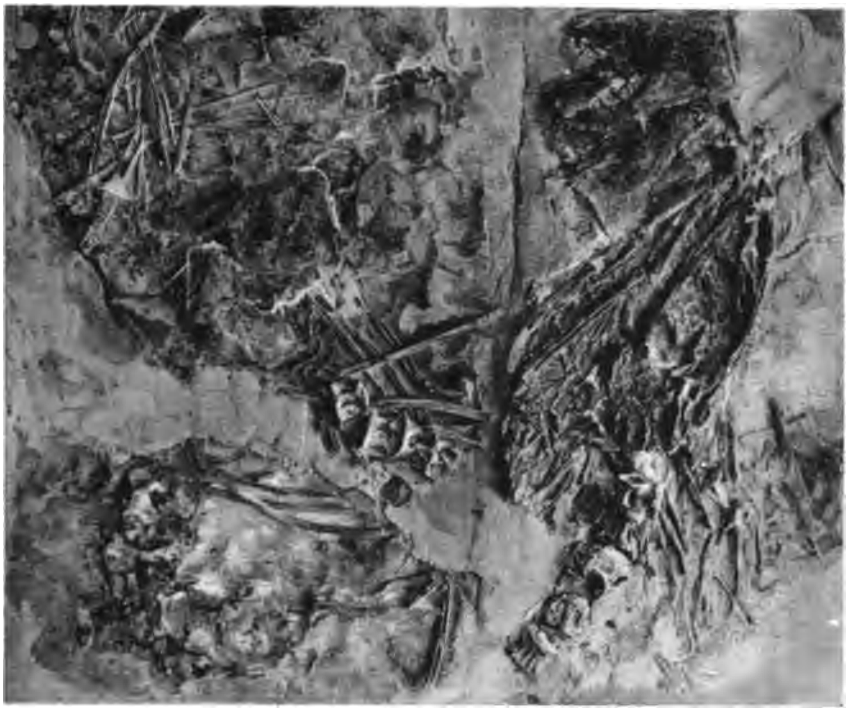
CRETACEOUS FISH SCALES



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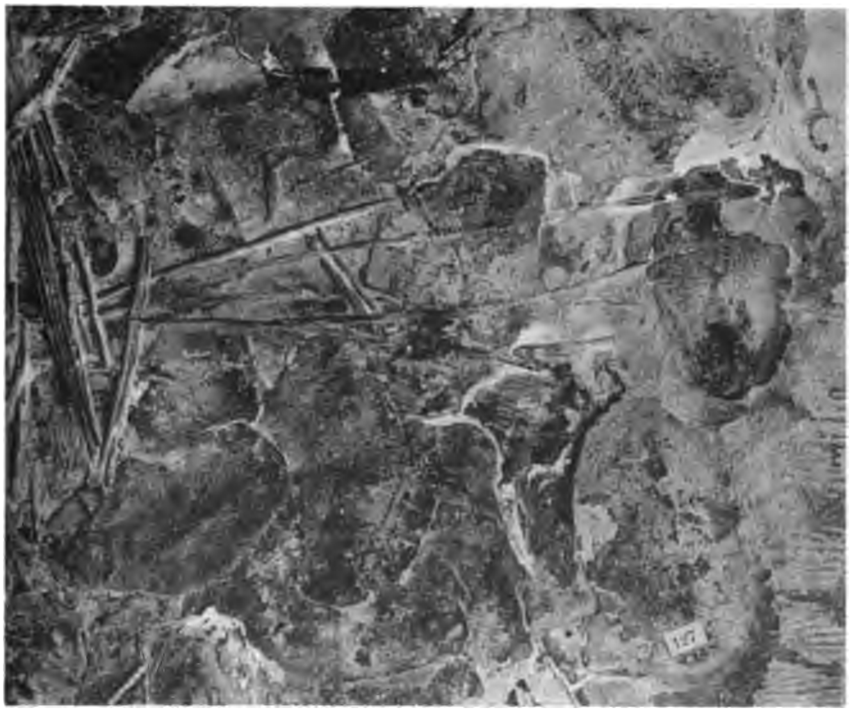

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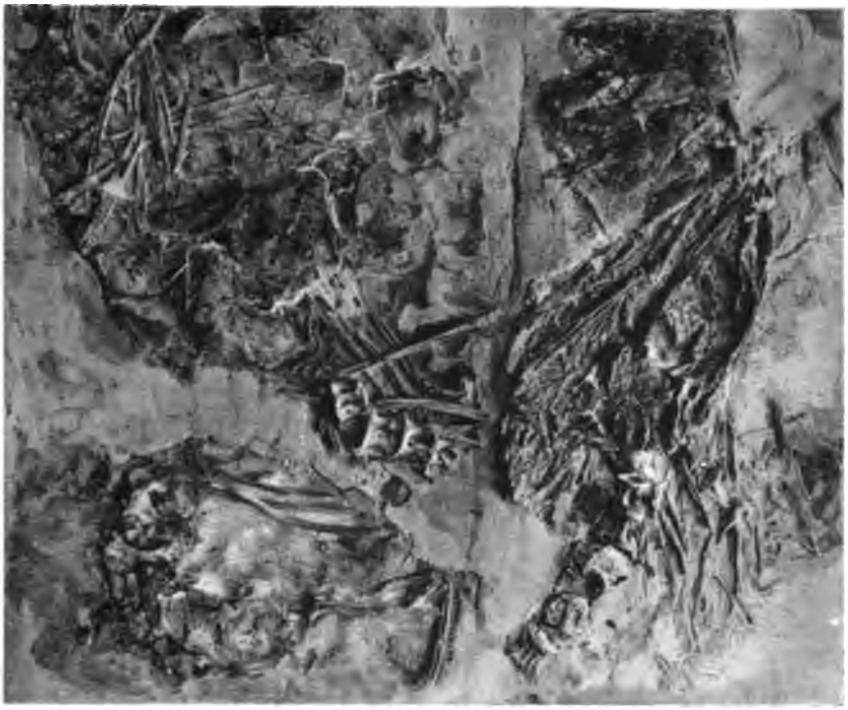
CRETACEOUS FISH SCALES

PLATE XXXIII.

FIGURES 1, 2. *Hypsodon audax* (Leidy) (p. 177):

1. Specimen showing several scales and parts of skeleton. University of Kansas collection.
2. Part of same specimen, more enlarged.



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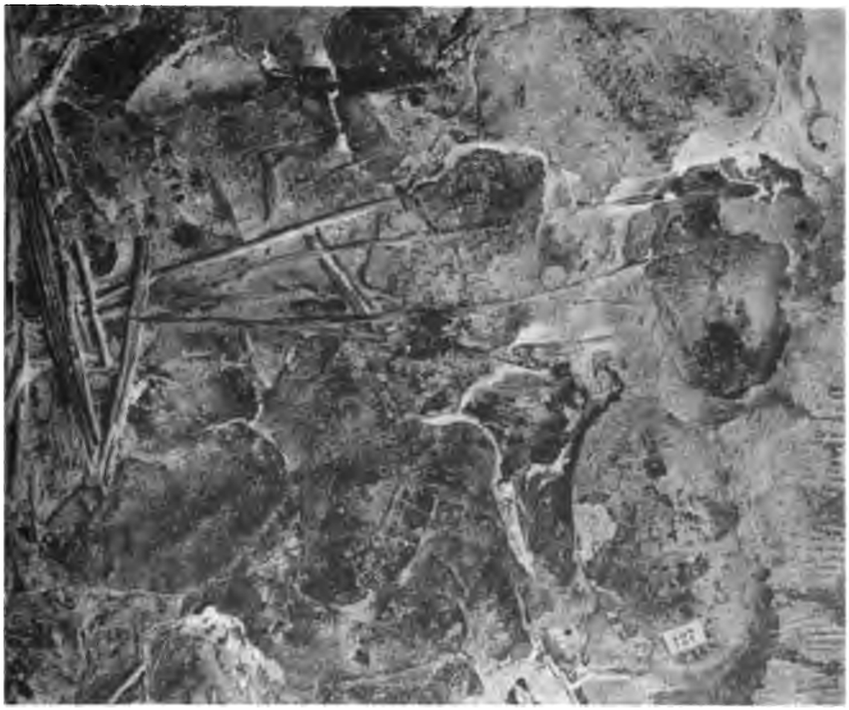

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CRETACEOUS FISH SCALES

PLATE XXXIV.

PLATE XXXIV.

FIGURE 1. *Chicolepis punctatus* Cockerell (p. 177). Type, × 3. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8682.

2. *Hypsodon lowii* (Stewart) Cockerell (p. 178). Scale, × 2. U. S. G. S. locality 7294. U. S. N. M. catalogue No. 8683.

3. *Ichthyodectes* sp. (p. 179). Lateral line scale, × 4. U. S. G. S. locality 2402. U. S. N. M. catalogue No. 8684.

4. *Ichthyodectes* sp. (p. 179). Lateral line scale, × 4. U. S. G. S. locality 7277. U. S. N. M. catalogue No. 8685.

5. *Pomolobus? chicoensis* Cockerell (p. 180). Type, × 10. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8686.

6–12. Cretaceous fish scales from Turkestan (p. 179). Copied from G. D. Romanowsky, Materialui dlya geologii Turkestanskago kraya, pts. 2, 3, 1884, 1890.

  6–8. *Hypsodon* sp. Figured as *Cladocyclus strehlensis* Geinitz. Op. cit., pt. 3, pl. 17, figs. 6a–c.

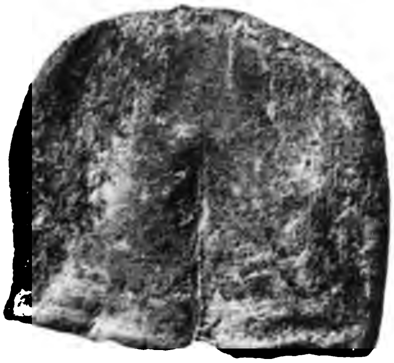
  9. *Hypsodon?* sp. Figured as *Osmeroides lewesiensis* (variety). Idem, pt. 2, pl. 23, fig. 4a.

  10. *Ichthyodectes* sp. Figured as *Cladocyclus strehlensis*. Idem, pt. 2, pl. 23, fig. 4b.

  11. *Ichthyodectes? pectinolepis*. Figured as *Osmeroides pectinolepis* Romanowsky. Idem, pt. 3, pl. 17, fig. 5.

  12. Undetermined scale. Figured as *Beryx* sp. Idem, pt. 3, pl. 17, fig. 4.

13. Fragment of Mowry shale, × 2, showing scales of *Erythrinolepis mowriensis*, *Leucichthyops vagans*, and *Holcolepis transversus* (pp. 182, 180, 175). U. S. G. S. locality 4896, north of Wolf Creek canyon, Big Horn Mountains, Wyo. U. S. N. M. catalogue No. 8687.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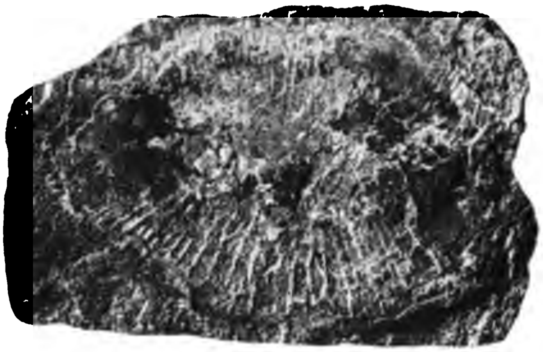
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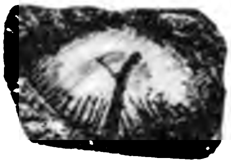
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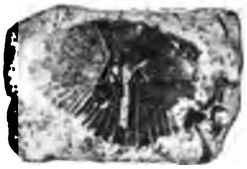
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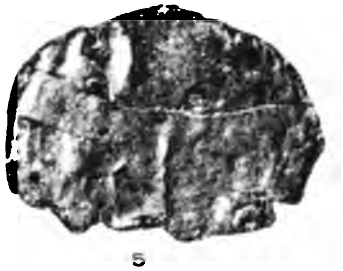
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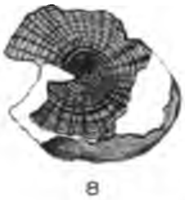
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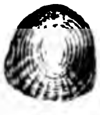
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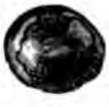
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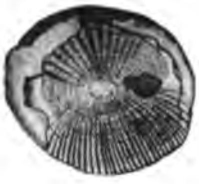
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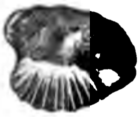
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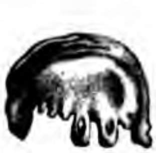
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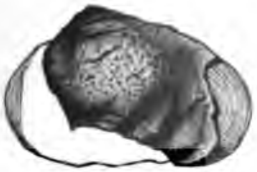
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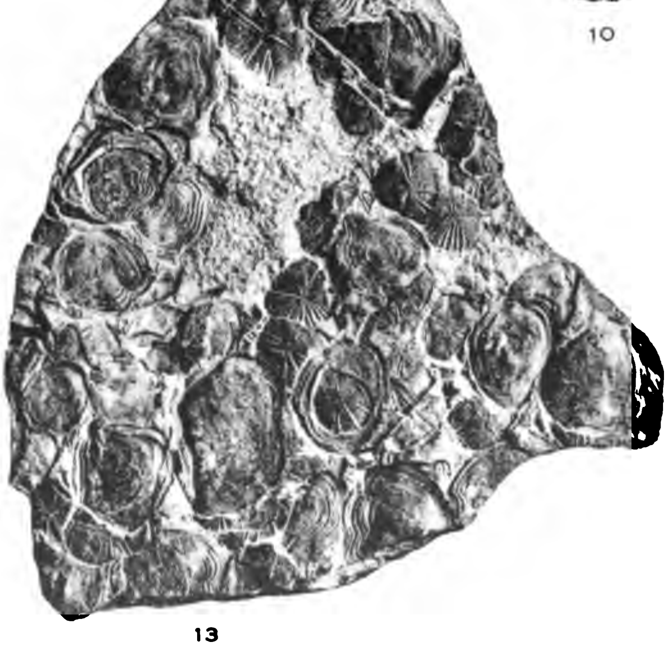

13

CRETACEOUS FISH SCALES

PLATE XXXII.

PLATE XXXII.

FIGURE 1. *Holcolepis obliquus* Cockerell (p. 175). Type, × 3. U. S. G. S. locality 4421. U. S. N. M. catalogue No. 8675.

2. *Holcolepis?* mandible, × 2 (p. 175). Carbon County, Wyo. U. S. N. M. catalogue No. 8676.

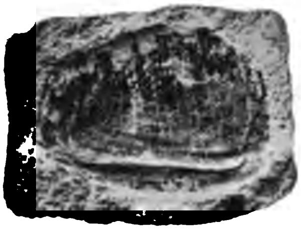
3. *Pachyrhizodus* scale from Cretaceous of England. After Woodward, Geol. Assoc. Proc., vol. 10, pl. 1, fig. 8, 1888 (p. 174).

4. *Helmintholepis vermiculatus* Cockerell (p. 176). Type, × 3. U. S. G. S. locality 9184. U. S. N. M. catalogue No. 8677.

5. *Hypsodon? granulosus* Cockerell (p. 178). Type, × 4. U. S. G. S. locality 4874. U. S. N .M .catalogue No. 8678.

6, 7. *Hyposodon? radiatulus* Cockerell (p. 178):
  6. Type, × 3. U. S. G. S. locality 5177, U. S. N. M. catalogue No. 8679.
  7. Latinucleate scale, × 3. U. S. G. S. locality 5174. U. S. N. M. catalogue No. 8680.

8. *Hypsodon audax* (Leidy). Scale, × 2 (p. 177). U. S. G. S. locality 8354. U. S. N. M. catalogue No. 8681.



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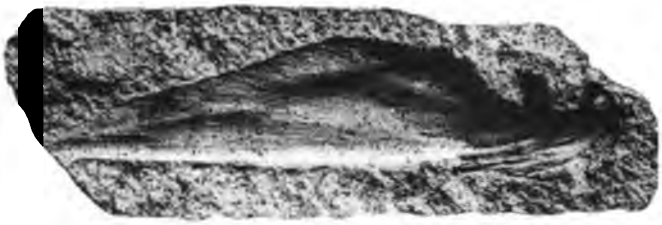

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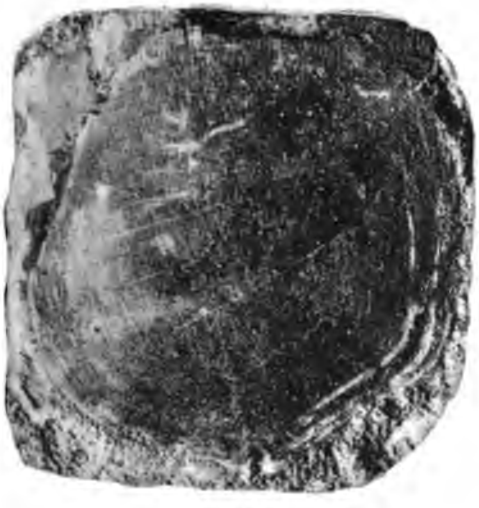

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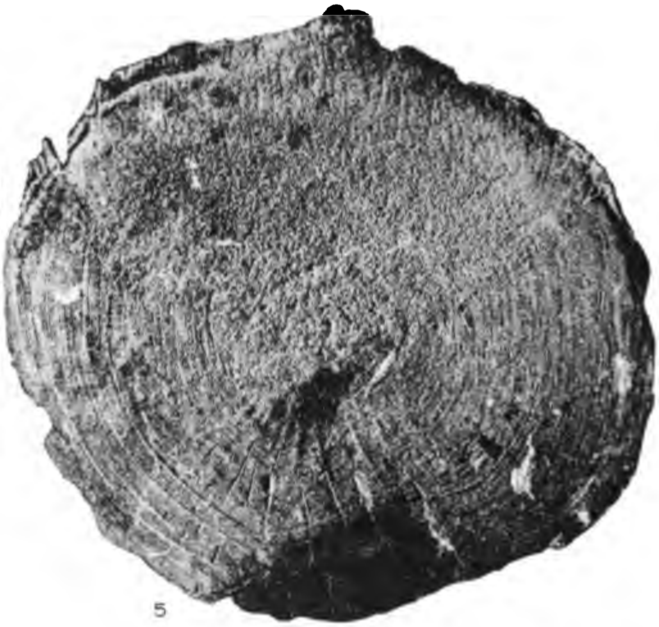

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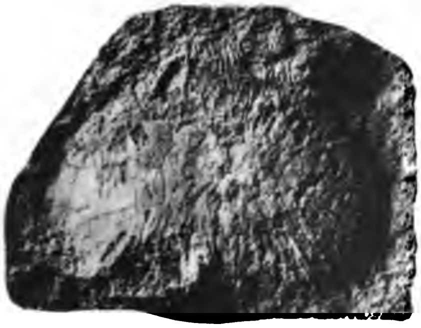

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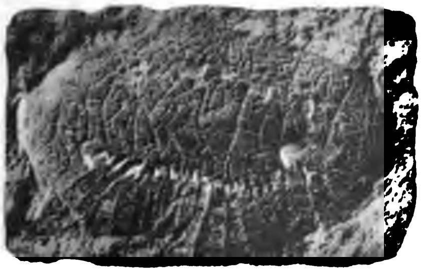

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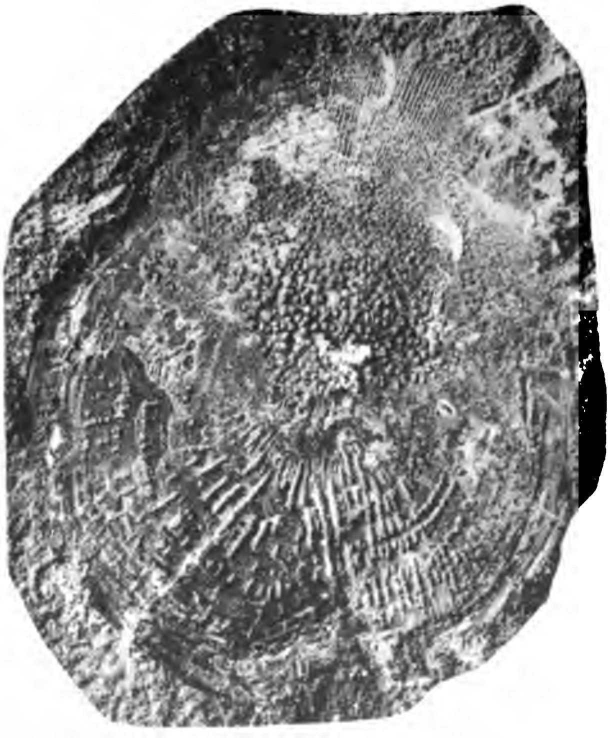


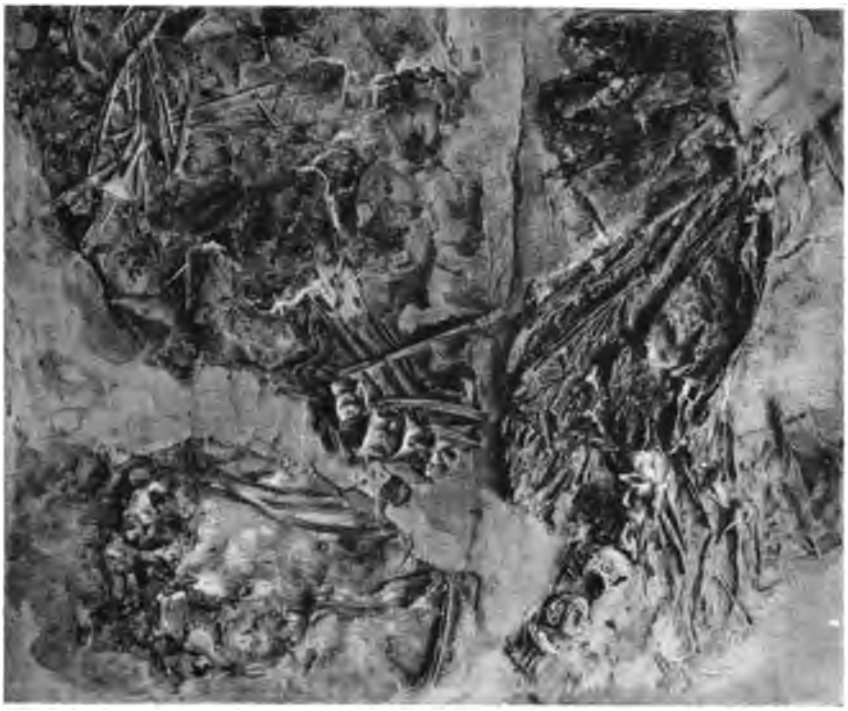
8

CRETACEOUS FISH SCALES

PLATE XXXIII.

FIGURES 1, 2. *Hypsodon audax* (Leidy) (p. 177):

1. Specimen showing several scales and parts of skeleton. University of Kansas collection.
2. Part of same specimen, more enlarged.



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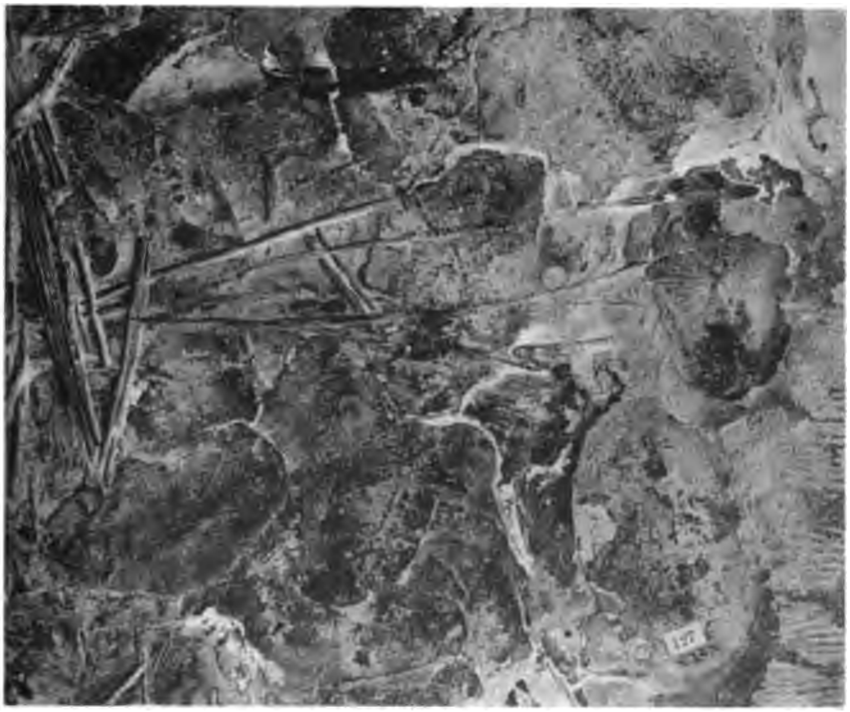

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CRETACEOUS FISH SCALES

PLATE XXXIV.

PLATE XXXIV.

FIGURE 1. *Chicolepis punctatus* Cockerell (p. 177). Type, × 3. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8682.

2. *Hypsodon lowii* (Stewart) Cockerell (p. 178). Scale, × 2. U. S. G. S. locality 7294. U. S. N. M. catalogue No. 8683.

3. *Ichthyodectes* sp. (p. 179). Lateral line scale, × 4. U. S. G. S. locality 2402. U. S. N. M. catalogue No. 8684.

4. *Ichthyodectes* sp. (p. 179). Lateral line scale, × 4. U. S. G. S. locality 7277. U. S. N. M. catalogue No. 8685.

5. *Pomolobus? chicoensis* Cockerell (p. 180). Type, × 10. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8686.

6-12. Cretaceous fish scales from Turkestan (p. 179). Copied from G. D. Romanowsky, Materialui dlya geologii Turkestanskago kraya, pts. 2, 3, 1884, 1890.

6-8. *Hypsodon* sp. Figured as *Cladocyclus strehlensis* Geinitz. Op. cit., pt. 3, pl. 17, figs. 6a-c.

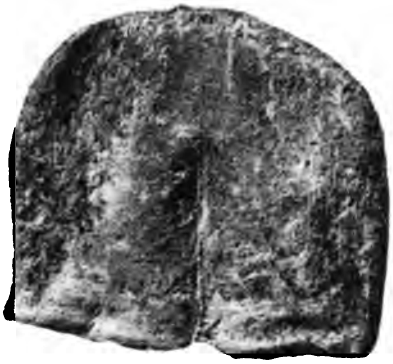
9. *Hypsodon?* sp. Figured as *Osmeroides lewesiensis* (variety). Idem, pt. 2, pl. 23, fig. 4a.

10. *Ichthyodectes* sp. Figured as *Cladocyclus strehlensis*. Idem, pt. 2, pl. 23, fig. 4b.

11. *Ichthyodectes? pectinolepis*. Figured as *Osmeroides pectinolepis* Romanowsky. Idem, pt. 3, pl. 17, fig. 5.

12. Undetermined scale. Figured as *Beryx* sp. Idem, pt. 3, pl. 17, fig. 4.

13. Fragment of Mowry shale, × 2, showing scales of *Erythrinolepis mowriensis*, *Leucichthyops vagans*, and *Holcolepis transversus* (pp. 182, 180, 175). U. S. G. S. locality 4896, north of Wolf Creek canyon, Big Horn Mountains, Wyo. U. S. N. M. catalogue No. 8687.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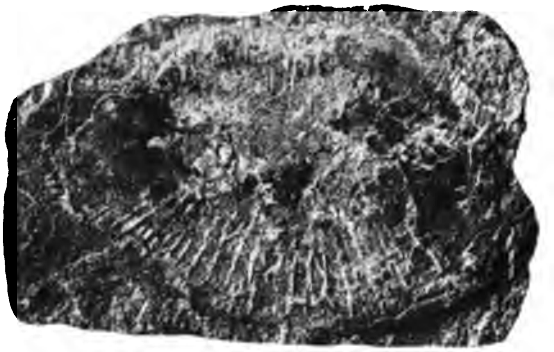
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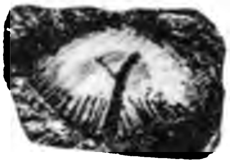
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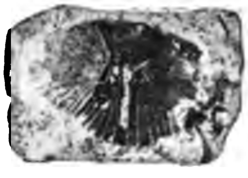
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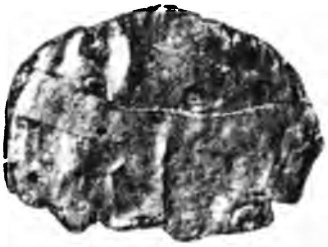
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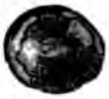
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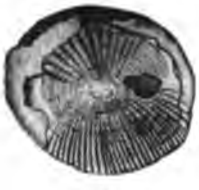
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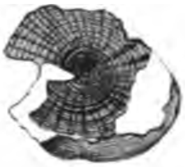
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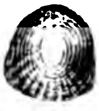
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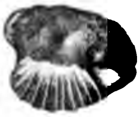
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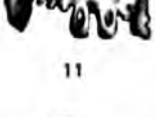
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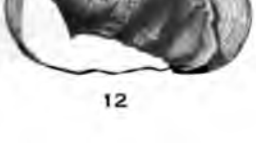
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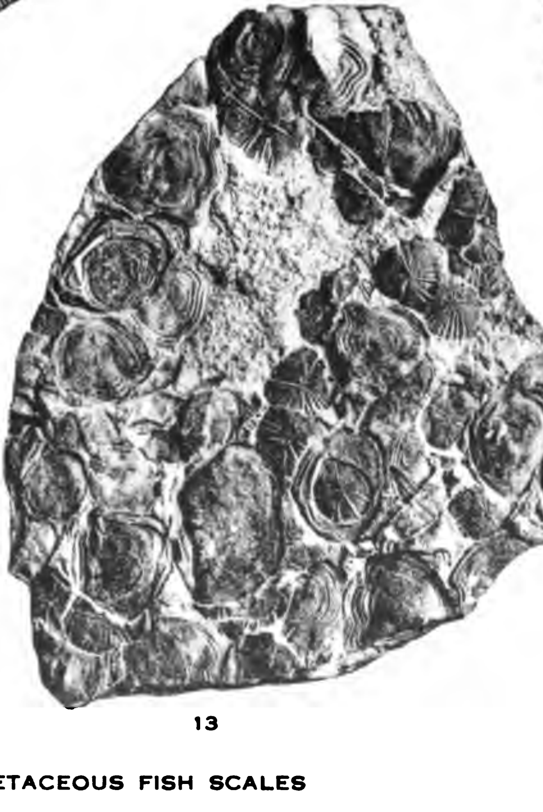

13

CRETACEOUS FISH SCALES

PLATE XXXV.

PLATE XXXV.

PLATE XXXV.

FIGURES 1-15. *Leucichthyops vagans* Cockerell (p. 180):

1. Type, × 4. U. S. G. S. locality 7095. U. S. N. M. catalogue No. 8688.

2, 3. Two scales, × 3. Carbon County, Wyo. U. S. N. M. catalogue Nos. 8689, 8690.

4. Scale, × 4. Black Hills, S. Dak. U. S. N. M. catalogue No. 8691.

5. Scale, × 3. U. S. G. S. locality 3880. U. S. N. M. catalogue No. 8692.

6. Scale, × 3. U. S. G. S. locality 7275. U. S. N. M. catalogue No. 8693.

7. Narrow scale, × 3. U. S. G. S. locality 6681. U. S. N. M. catalogue No. 8694.

8. Scale, × 4. U. S. G. S. locality 8916. U. S. N. M. catalogue No. 8695.

9. Narrow scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8696.

10. Lateral line scale, × 4. U. S. G. S. locality 6682. U. S. N. M. catalogue No. 8697.

11. Lateral line scale, × 4. U. S. G. S. locality 7095. U. S. N. M. catalogue No. 8698.

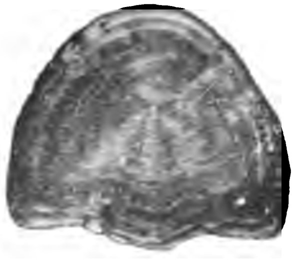
12. Lateral line scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8699.

13. Lateral line scale, × 4. U. S. G. S. locality 7100. U. S. N. M. catalogue No. 8700.

14. Lateral line scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8701.

15. Latinucleate scale, × 4. Black Hills, S. Dak. U. S. N. M. catalogue No. 8702.

16. *Cyclolepis stenodinus* Cockerell (p. 181). Type, × 4. U. S. G. S. locality 9190. U. S. N. M. catalogue No. 8703.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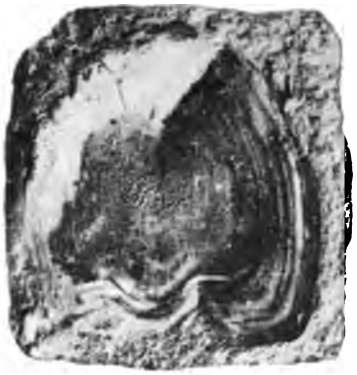
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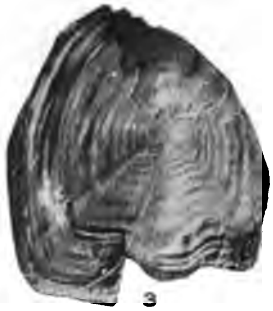
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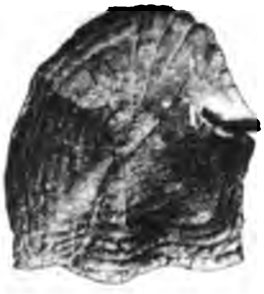
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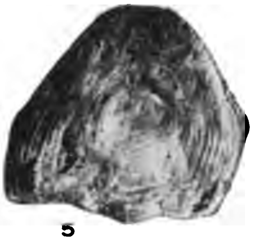
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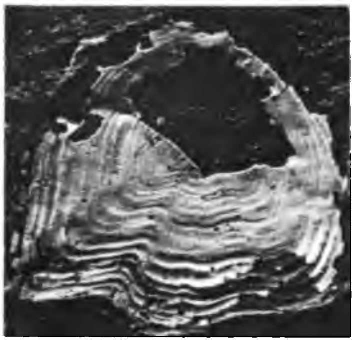
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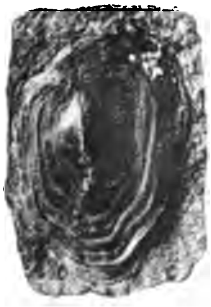
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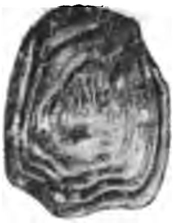
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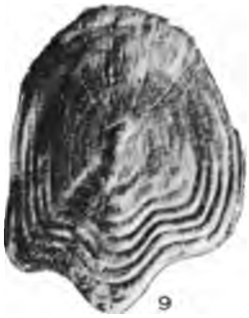
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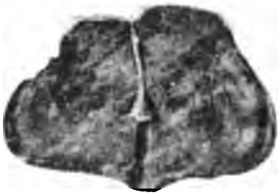
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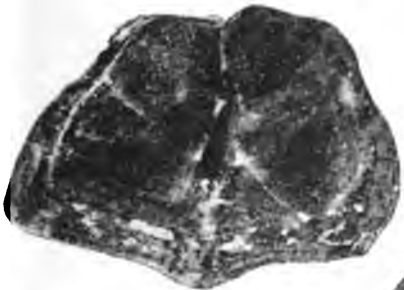
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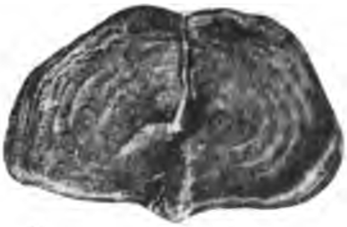
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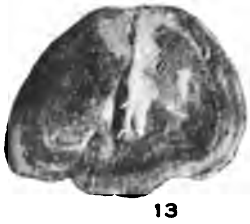
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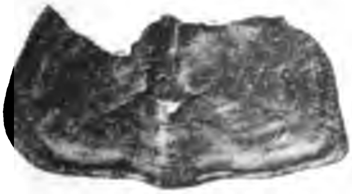
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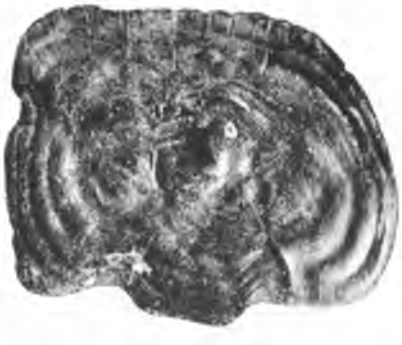
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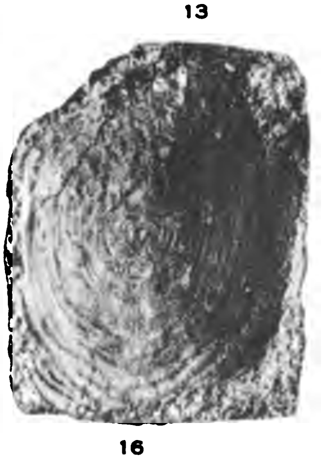
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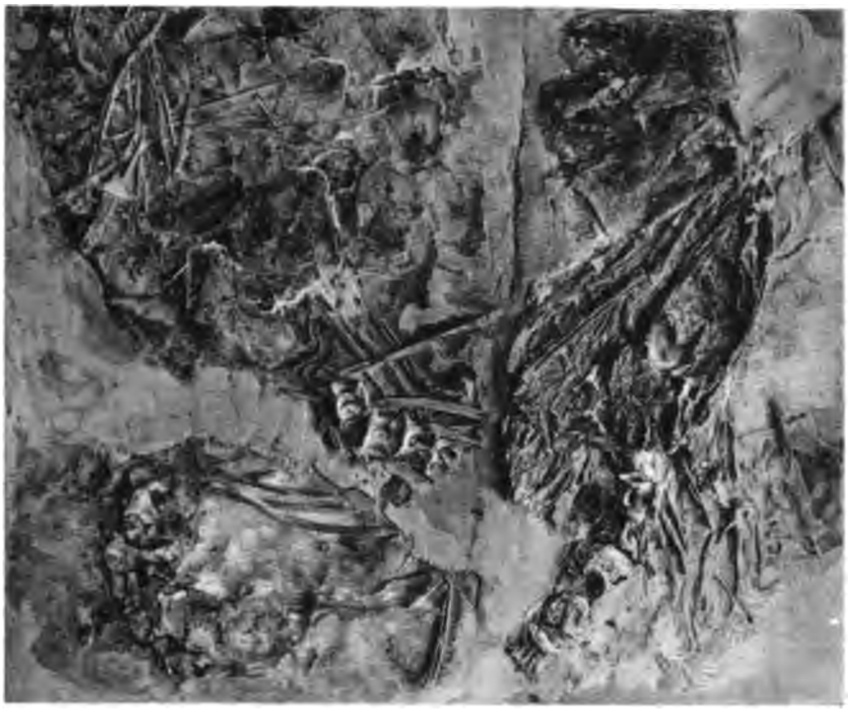
CRETACEOUS FISH SCALES

PLATE XXXVI.

PLATE XXXIII.

FIGURES 1, 2. *Hypsodon audax* (Leidy) (p. 177):

1. Specimen showing several scales and parts of skeleton. University of Kansas collection.
2. Part of same specimen, more enlarged.



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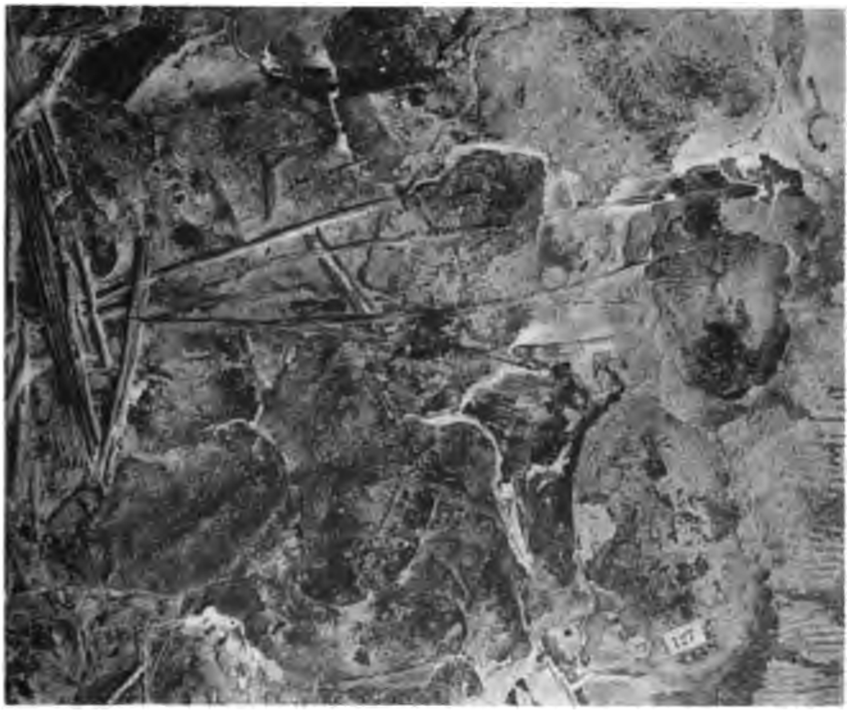

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CRETACEOUS FISH SCALES

PLATE XXXIV.

PLATE XXXIV.

FIGURE 1. *Chicolepis punctatus* Cockerell (p. 177). Type, × 3. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8682.

2. *Hypsodon lowii* (Stewart) Cockerell (p. 178). Scale, × 2. U. S. G. S. locality 7294. U. S. N. M. catalogue No. 8683.

3. *Ichthyodectes* sp. (p. 179). Lateral line scale, × 4. U. S. G. S. locality 2402. U. S. N. M. catalogue No. 8684.

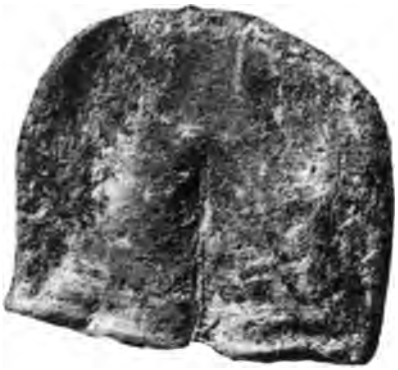
4. *Ichthyodectes* sp. (p. 179). Lateral line scale, × 4. U. S. G. S. locality 7277. U. S. N. M. catalogue No. 8685.

5. *Pomolobus? chicoensis* Cockerell (p. 180). Type, × 10. U. S. G. S. locality 7030. U. S. N. M. catalogue No. 8686.

6–12. Cretaceous fish scales from Turkestan (p. 179). Copied from G. D. Romanowsky, Materialui dlya geologii Turkestanskago kraya, pts. 2, 3, 1884, 1890.

- 6–8. *Hypsodon* sp. Figured as *Cladocyclus strehlensis* Geinitz. Op. cit., pt. 3, pl. 17, figs. 6a–c.
- 9. *Hypsodon?* sp. Figured as *Osmeroides lewesiensis* (variety). Idem, pt. 2, pl. 23, fig. 4a.
- 10. *Ichthyodectes* sp. Figured as *Cladocyclus strehlensis*. Idem, pt. 2, pl. 23, fig. 4b.
- 11. *Ichthyodectes? pectinolepis*. Figured as *Osmeroides pectinolepis* Romanowsky. Idem, pt. 3, pl. 17, fig. 5.
- 12. Undetermined scale. Figured as *Beryx* sp. Idem, pt. 3, pl. 17, fig. 4.

13. Fragment of Mowry shale, × 2, showing scales of *Erythrinolepis mowriensis*, *Leucichthyops vagans*, and *Holcolepis transversus* (pp. 182, 180, 175). U. S. G. S. locality 4896, north of Wolf Creek canyon, Big Horn Mountains, Wyo. U. S. N. M. catalogue No. 8687.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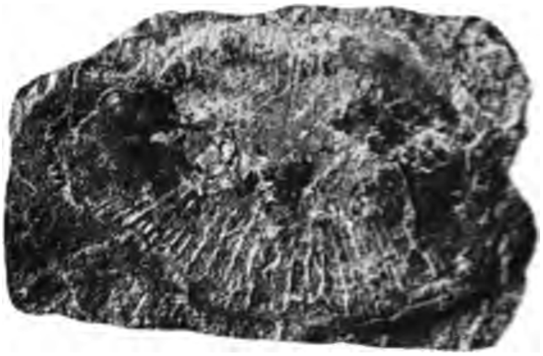
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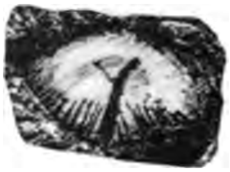
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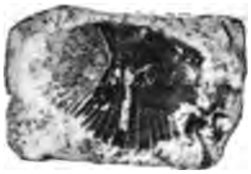
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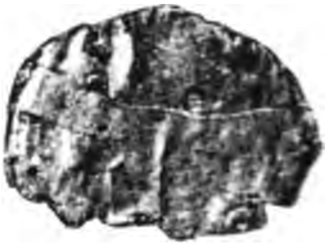
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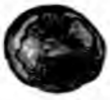
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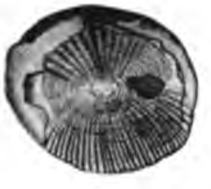
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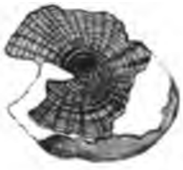
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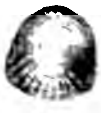
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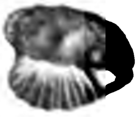
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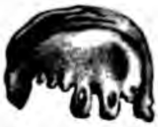
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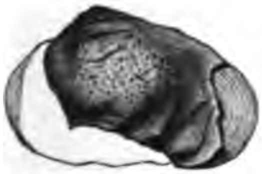
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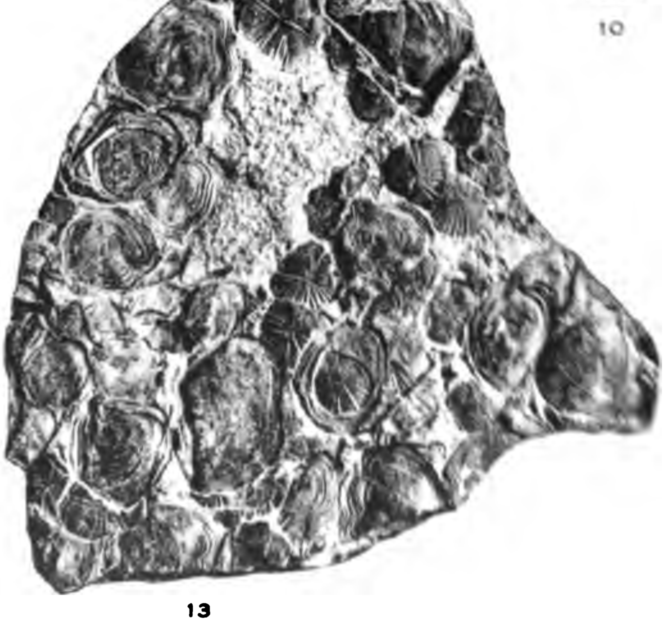
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CRETACEOUS FISH SCALES

PLATE XXXV.

PLATE XXXV.

FIGURES 1-15. *Leucichthyops vagans* Cockerell (p. 180):

1. Type, × 4. U. S. G. S. locality 7095. U. S. N. M. catalogue No. 8688.

2, 3. Two scales, × 3. Carbon County, Wyo. U. S. N. M. catalogue Nos. 8689, 8690.

4. Scale, × 4. Black Hills, S. Dak. U. S. N. M. catalogue No. 8691.

5. Scale, × 3. U. S. G. S. locality 3880. U. S. N. M. catalogue No. 8692.

6. Scale, × 3. U. S. G. S. locality 7275. U. S. N. M. catalogue No. 8693.

7. Narrow scale, × 3. U. S. G. S. locality 6681. U. S. N. M. catalogue No. 8694.

8. Scale, × 4. U. S. G. S. locality 8916. U. S. N. M. catalogue No. 8695.

9. Narrow scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8696.

10. Lateral line scale, × 4. U. S. G. S. locality 6682. U. S. N. M. catalogue No. 8697.

11. Lateral line scale, × 4. U. S. G. S. locality 7095. U. S. N. M. catalogue No. 8698.

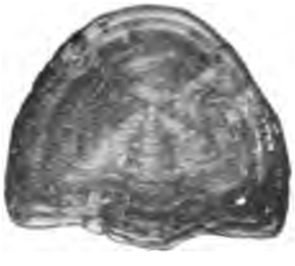
12. Lateral line scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8699.

13. Lateral line scale, × 4. U. S. G. S. locality 7100. U. S. N. M. catalogue No. 8700.

14. Lateral line scale, × 4. U. S. G. S. locality 7110. U. S. N. M. catalogue No. 8701.

15. Latinucleate scale, × 4. Black Hills, S. Dak. U. S. N. M. catalogue No. 8702.

16. *Cyclolepis stenodinus* Cockerell (p. 181). Type, × 4. U. S. G. S. locality 9190. U. S. N. M. catalogue No. 8703.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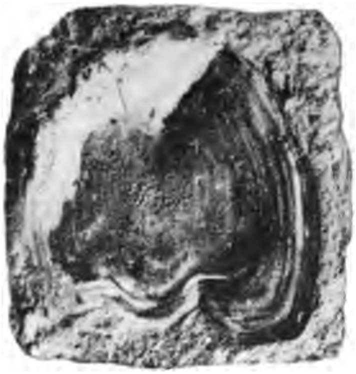
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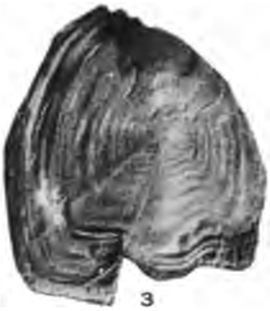
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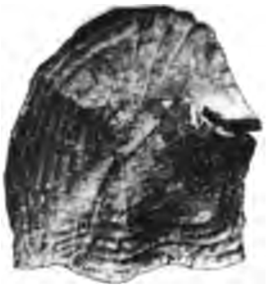
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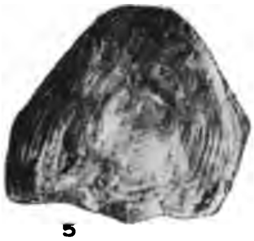
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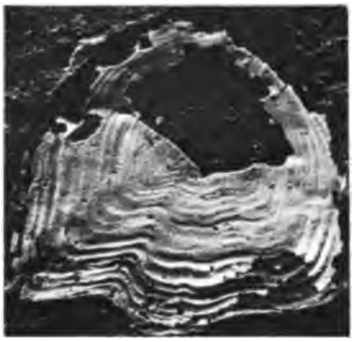
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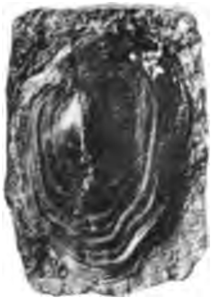
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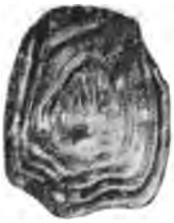
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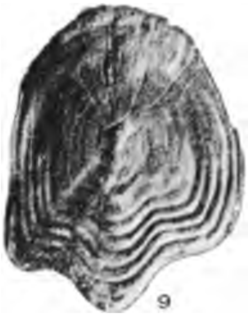
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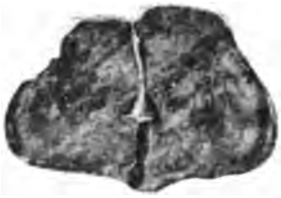
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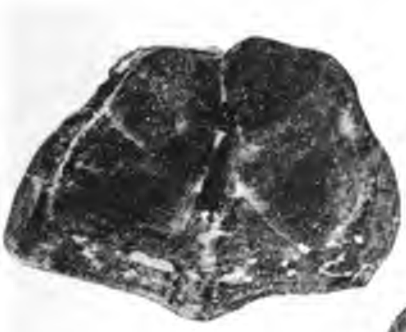
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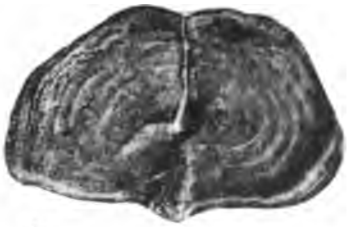
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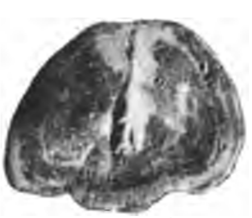
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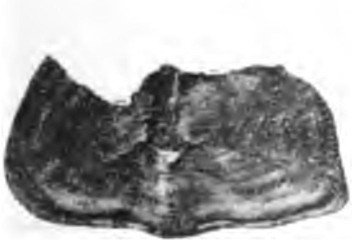
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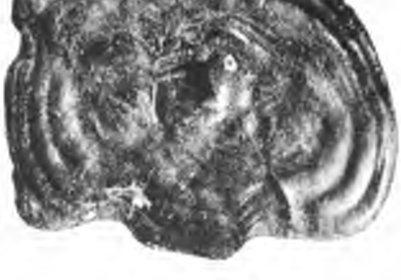
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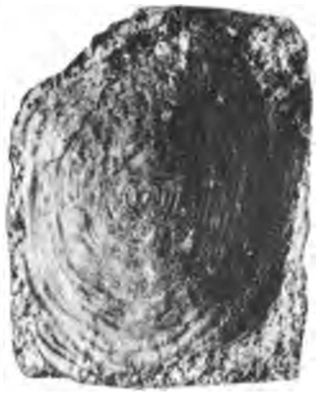
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CRETACEOUS FISH SCALES

PLATE XXXVI.

formations known collectively as the Wabaunsee group. This group is underlain by the Shawnee, Douglas, Lansing, Kansas City, Pleasanton, and Henrietta groups, and the Cherokee shale, which have themselves been subdivided into the formations shown in the columnar section. Although many of these formations, especially the limestones, are remarkably persistent and may be traced throughout most of eastern Kansas, the Pennsylvanian series as a whole, together with the lower half of the Permian, constitutes a broad lithologic unit. All the upper and middle Pennsylvanian rocks consist of alternating beds of shale, limestone, and sandstone. The shale is by far the most abundant; the limestone beds are generally less than 25 feet thick, and the sandstones are commonly thin and discontinuous. The Cherokee formation differs somewhat from the remainder of the series in that it contains fewer limestone beds and more sandstones, which, though inconspicuous as stratigraphic units, are of great economic importance as oil sands.

The Mississippian series, which crops out in the extreme southeast corner of Kansas, consists chiefly of crystalline limestone with a considerable proportion of hard chert. In eastern Kansas the series is not more than 350 feet thick, and along the granite ridge on the west edge of the oil and gas region the Mississippian is entirely absent. It has not been encountered by wells drilled west of this belt, though it may be present locally in western Kansas, as suggested in the stratigraphic section in Plate II. The upper surface of the Mississippian in eastern Kansas is very irregular, varying in elevation as much as 75 feet in a distance of half a mile, but its general inclination is not markedly different from that of the overlying Pennsylvanian beds. The Mississippian rests unconformably on the older Paleozoic formations.

PRE-CARBONIFEROUS FORMATIONS.

Beneath the oil-bearing rocks of the Carboniferous system lies a considerable thickness of Paleozoic formations which rest directly on the granite of the pre-Cambrian basement. These older formations do not crop out in Kansas but may be studied in the Ozark uplift of Missouri and on the Rocky Mountain front. On the northern and western flanks of the Ozark uplift Silurian and Devonian formations are exposed, but as these formations are absent in most of the Rocky Mountain area, they may not underlie much of the Kansas region. The chief formations involved in the Ozark uplift are of Cambrian and Ordovician age and consist of 2,000 to 2,500 feet of dolomite and limestone, with some sandstone and shale. In Colorado, however, the equivalent formations have a maximum thickness of only about 300 feet and in many localities they are lacking. It is evident, therefore, that the Cambrian and Ordovician beds become much thinner toward the west, though they doubtless underlie much of the Kansas region. As these beds were laid down directly on the granite basement and were subjected to uplift and erosion before the deposition of the Mississippian sediments their thickness from place to place presumably depends in part on the contour of the granite floor.

The granite and other crystalline rocks forming the basement on which the sedimentary formations described above were deposited are not exposed in Kansas but crop out in eastern Missouri, in the Rocky Mountains, in the Wichita and Arbuckle uplifts of southern Oklahoma, and in the southern parts of Minnesota and South Dakota. It was formerly supposed that the pre-Cambrian rocks underlie the Kansas region only at great depth, but drilling within the last few years has revealed the presence of granite at comparatively shallow depths in a zone extending through east-central Kansas and at somewhat greater depths at several isolated localities in the eastern part of the State.[31] The coarse grain of the crystalline rocks and the unmetamorphosed character of the sediments immediately overlying them indicate beyond question that they are a part of the original basement and are not recent intrusions.

The granite lies nearest to the surface in northern Kansas, where it is encountered at a depth of only about 600 feet, but as far to the south as Chase County it lies in general within 2,000 feet of the surface. In that locality it appears to drop off sharply, but it is reported that granite has recently been encoun-

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[31] A comprehensive description of these crystalline rocks is given by R. C. Moore and W. P. Haynes (op. cit., pp. 140-173).

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tered at a depth of about 4,000 feet in the Augusta field, in Butler County. The available information regarding this so-called granite ridge is summarized in figure 3, which shows the wells that have encountered granite and the depth at which they found it, and also the location and depth of other wells in this belt that did not reach the granite. As shown by the structure section, all the Mississippian and older formations and much of the Pennsylvanian are lacking in the northern part of the granite belt, though in Butler County the whole of the Pennsylvanian and Mississippian series are probably present.

The relations of the sedimentary formations to the granite ridge indicate that the ridge was formed prior to the Pennsylvanian epoch. The small size of the elevated mass suggests, however, that it could not have remained long above sea level without being reduced by erosion, and furthermore, the Mississippian and older formations of eastern Kansas contain little clastic material, such as a near-by granite land mass would furnish; hence it is thought that the ridge was elevated at the end of the Mississippian epoch. The Cambrian, Ordovician, and Mississippian formations were probably laid down throughout this area, but at the end of Mississippian time there was a period of uplift and erosion, as indicated by the uneven upper surface of the Mississippian itself. Differential uplift at this time probably led to the formation of the long, narrow granite ridge, and during the ensuing period of erosion all the sedimentary formations were apparently removed from this elevated area. When resubmergence of the surrounding country took place at the beginning of Pennsylvanian time most of the granite ridge remained an island, and it was not completely submerged until the end of the Shawnee epoch.

As shown in figure 3, a well in Riley County, distinctly to the west of the main ridge, found granite at a depth of 2,385 feet, which may indicate simply a shoulder on the western slope of the main ridge or may represent another and distinct protuberance of the granite basement. Similarly a well in Woodson County, far to the east of the main ridge, found granite at 2,585 feet, or only about 700 feet beneath the base of the Mississippian. A well at Paola, Miami County, is reported to have reached granite at 2,260 feet, or about 1,000 feet below the Mississippian. On the other hand, a well at Iola, only about 20 miles east of the Woodson County well, entered the Mississippian at 1,040 feet, and though it was drilled to 3,434 feet no granite was recorded. It seems, therefore, that the granite basement is irregular in contour and that there may be other though less prominent ridges elsewhere in eastern Kansas.

As the main granite ridge is coincident with the western border of the helium-rich area (though also extending far to the north and probably to the south of it), its structural relations are of special interest in connection with the source of the helium. The great length and small width of the elevated area and also the dense and crystalline character of the rock involved strongly suggest that the ridge is an elevated fault block, or at least that one of its sides, probably the eastern, is determined by a fault. A. E. Fath,[a] of the Geological Survey, who has given special attention to the mechanics of the structure of the Mid-Continent region, is in favor of this view and believes, moreover, that the basement rocks throughout the region are probably extensively fissured and that recent movements along these fissures have produced the many minor wrinkles that characterize the surface rocks of the region. Among his reasons for this belief are the following: (1) The rocks above the granite ridge lie in very prominent anticlines which in places represent structural elevations of over 200 feet. This fold is too large to be explained by differential settling and can best be accounted for by thrust from below. (2) The presence of granite at moderate depth at several isolated localities in eastern Kansas suggests that there may be elsewhere similar elevations in the granite floor. (3) In Kansas and Oklahoma there are many anticlines parallel to the granite ridge which, though representing uplifts of only a hundred feet or so, can be traced across several counties. It is unreasonable to suppose that such regular and persistent structural features were produced by lateral thrusts which, so far as present knowledge indicates, must have originated several hundred miles east and west of the area. (4) The surface rocks in parts of northern Oklahoma

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[a] Personal communication. Mr. Fath discusses his views at length in a paper entitled "The origin of the faults, anticlines, and buried 'granite ridge' of the northern part of the Mid-Continent oil and gas field" (U. S. Geol. Survey Prof. Paper 128, pp. 75-84, 1920).

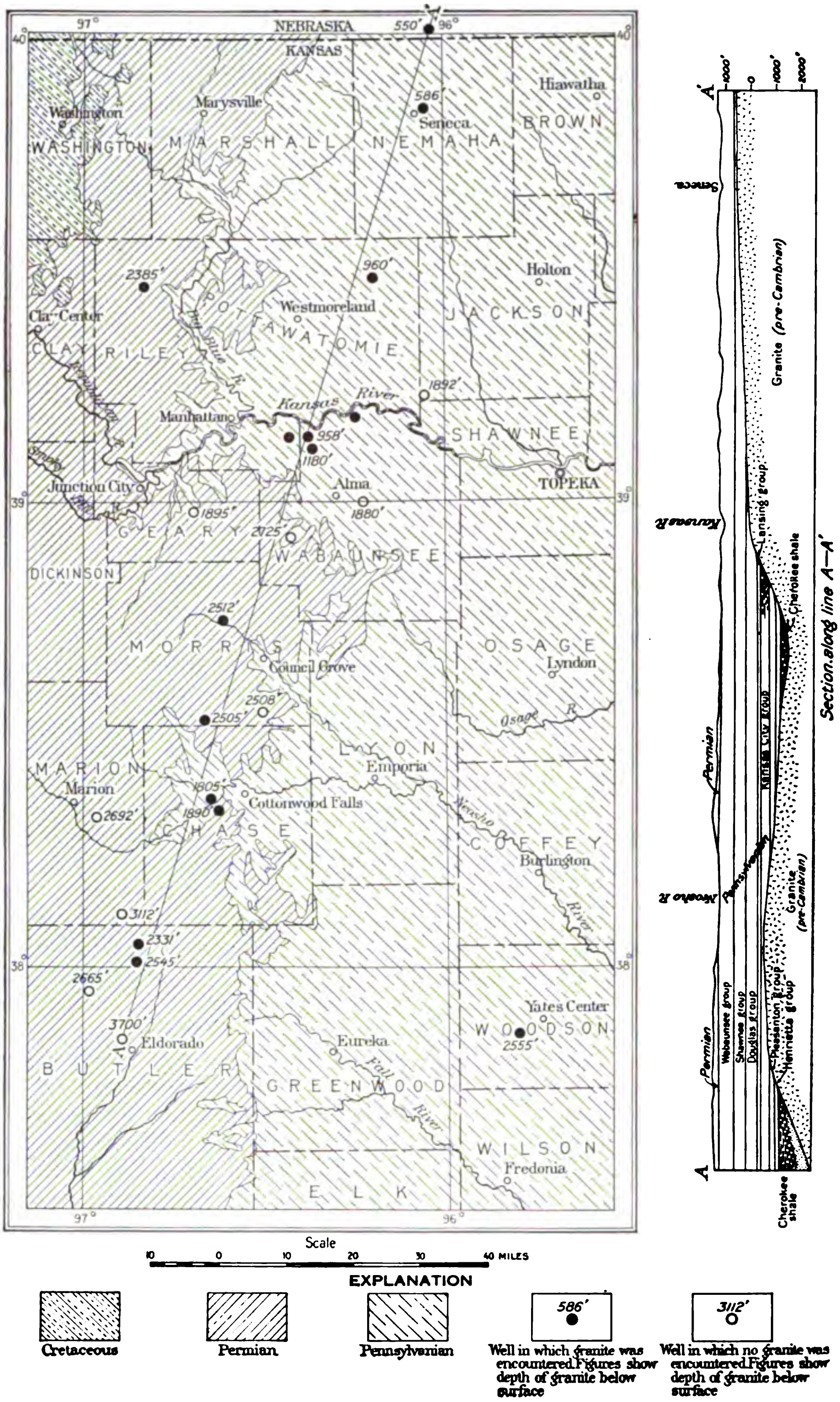


FIGURE 3.—Map of portion of eastern Kansas showing depth and relations of the granite ridge.

are broken by many small parallel faults which occur in zones that may be traced for many miles and that are essentially parallel to the granite ridge and to the main anticlines. These faults can also best be explained as faint surface reflections of more extensive movements of the pre-Cambrian floor.

Although the contour of the granite ridge itself forms the most direct basis for assuming a fault in the pre-Cambrian rocks, the lines of evidence brought together by Mr. Fath thus furnish excellent reasons for suspecting the presence of many similar fault lines. This possibility is of special interest in connection with the source of the helium, as discussed on pages 66–67.

STRATIGRAPHIC DISTRIBUTION OF THE HELIUM.

Viewed broadly, the helium content of natural gas is related to the stratigraphic position of the producing sands, though the relation is by no means precise. Cady and McFarland, in their report on the helium-bearing gas of Kansas, presented a map showing "iso-helium" lines, which, as they pointed out, had a general similarity in trend to the outcrops of the geologic formations. The numerous analyses now available indicate, however, that such lines can not be drawn, for the factors of the geographic location and depth beneath the surface must be taken into account, as well as the factor of stratigraphic position.

The generalized structure section on Plate I shows the helium content and relative stratigraphic position of a number of natural gases from southern Kansas and northern Oklahoma. It will be noted at once that the gases richest in helium occur in middle and upper Pennsylvanian strata. The one sample of Mississippian gas collected in the fields adjacent to the line of the section contained only 0.08 per cent of helium. Three samples of gas from the Cherokee shale contained, as shown in the section, less than 0.1 per cent of helium. The gases of the overlying Henrietta and Pleasanton groups are considerably richer, three samples averaging 0.47 per cent. The Kansas City group, however, is the lowest in which gas carrying more than 1 per cent of helium has been found, and similarly rich gases occur in all the overlying Pennsylvanian beds. The Permian gases, on the other hand, are poor in helium, the two samples plotted in the section showing only 0.27 and 0.1 per cent.

In a broad sense, therefore, gases containing more than 0.5 per cent of helium seem to occur only in the strata between the top of the Wabaunsee group and the base of the Kansas City group, a stratigraphic range of about 2,000 feet. If this conclusion is correct it follows that the area of gas carrying more than 0.5 per cent of helium is bounded on the east by the line along which the Kansas City group lies at a depth of 200 feet or so, for commercial accumulations of gas can hardly be expected at depths shallower than this. The western limit of the area, however, is not determined by stratigraphic considerations, but it is defined at present simply by the western limit of oil and gas development. Should this development be extended a considerable distance farther west, it may be presumed that the factor of depth will determine the western limit of the helium-rich area, for, as described below, gases rich in helium apparently do not occur at depths greater than about 1,600 feet. The top of the Pennsylvanian series probably reaches this depth within 25 miles to the west of the known helium-rich area.

Although stratigraphic considerations serve to define the outer limits of the helium-bearing zone, it is evident that the helium content of the gases within the zone varies greatly. Individual samples from approximately the same horizon in the Augusta field range in helium content from 0.2 to 1.1 per cent, and samples from the Sedan field from 1 to 2 per cent. Similarly the gas at Otto, Kans., which carries 1.04 per cent of helium, occurs at about the same horizon as the gases of the Pearson and Myers fields, Oklahoma, which average only 0.48 and 0.37 per cent. Furthermore, the north and south limits of the helium-rich area are not related to stratigraphy or structure, and gases within the area that carry more than 2 per cent of helium occur at the same general horizon as those outside that carry less than 0.25 per cent.

Although the helium-rich gas of the Mid-Continent area thus occurs characteristically in upper and middle Pennsylvanian formations, it is found in those formations only in a certain area, and even in that area its vertical and horizontal distribution is irregular.

VARIATION IN HELIUM CONTENT WITH DEPTH.

The helium content of gases in the Mid-Continent field is generally related to the depth at which the gases occur, deep gases being poorer in helium than shallow ones. The gas occurring at a depth of 1,475 feet at Otto, Kans., contains about 1 per cent of helium, but nowhere else in the region is equally rich gas known to occur below 1,200 feet. On the other hand, gas carrying more than 1.75 per cent of helium has been discovered only in the Augusta, Dexter, and Sedan fields, and in all of these it occurs at depths of less than 600 feet. The gases richest in helium are high in nitrogen and being thus of little value for heating are known in the fields as "wind gas"; and it is generally recognized by oil and gas operators that wind gas occurs characteristically at shallow depth.

In most fields in which there are two or more gas sands the shallowest gas is richest in helium. At Augusta, for example, the 600-foot gas contains 2 per cent of helium and the 1,500-foot gas averages only 0.5 per cent. At Eldorado the 900-foot gas averages 1.2 per cent, and the 1,200-foot gas 1 per cent. At Sedan the 400-foot gas averages more than 1.5 per cent, whereas the 700-foot gas carries only about 1 per cent.

Owing to the fact that the dip of the strata throughout the Mid-Continent field is comparatively gentle, vertical and stratigraphic distances are about the same, and in some localities it is difficult to decide whether the helium content of the gas is influenced more by its depth beneath the surface or by its stratigraphic position. It seems clear, however, that the gas from a given formation is likely to be richer in helium in localities where the formation lies at shallow depth than where it occurs at greater depth. This is shown in the structure section on Plate I, though it must be admitted that the relation is rather irregular and vague. On the other hand, in some localities the factor of depth seems to be less important than that of stratigraphic position. In the Billings field, for example, the 500-foot gas which occurs in the Permian contains only 0.1 per cent of helium, whereas the 1,000-foot gas, which probably occurs in the uppermost Pennsylvanian strata, carries 0.39 per cent. Similarly the gas of the Cherokee shale in eastern Kansas seems to be uniformly poor in helium, though it occurs in many localities at shallow depths.

NORTH TEXAS REGION.

LOCATION.

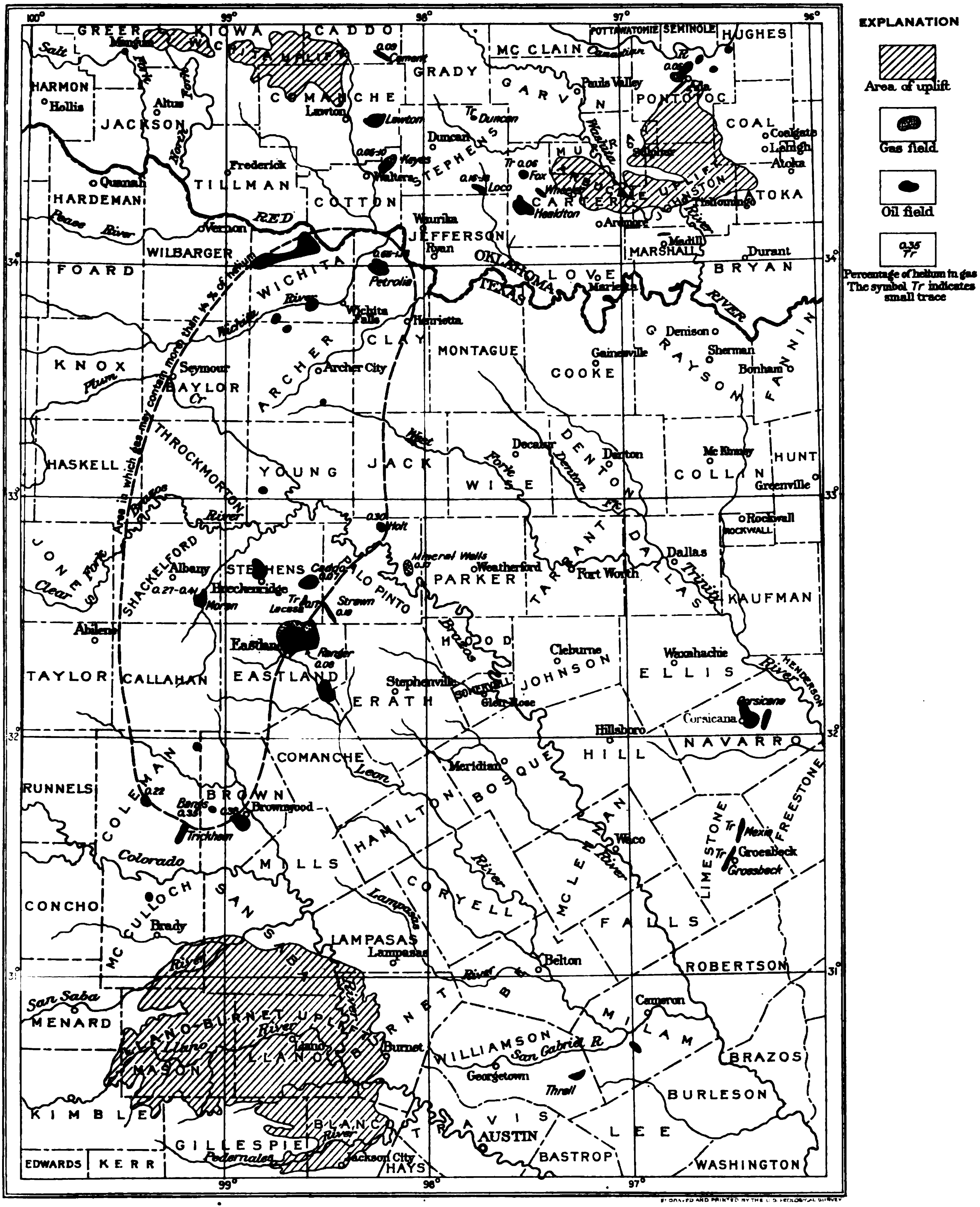
The only field in Texas in which gas containing more than 0.5 per cent of helium has yet been found is the Petrolia field in Clay County. Gas carrying more than 0.25 per cent of helium, however, occurs throughout a considerable area lying to the south and southwest of Petrolia and extending from that field to Coleman and Brown counties. This area lies mostly to the west of the great north Texas oil and gas fields, but it is a district in which prospecting and development are now very active. It is probable, therefore, that the boundaries of the area as shown on Plate III, especially the western boundary, will be changed by future developments.

All sources of supply in northern and central Texas and southern Oklahoma were sampled at the time of the writer's visit, in July, 1918. The location of the gas fields and the helium content of their product are shown in more detail in Plate III.

GEOLOGY.

The north Texas oil and gas region lies near the eastern rim of the great Carboniferous basin which underlies most of western Texas and eastern New Mexico. Toward the west this basin extends northward without interruption into western Oklahoma and Kansas, but on the east it is partly separated from the Mid-Continent basin by the Wichita and Arbuckle uplifts of southern Oklahoma. The north Texas petroleum region thus lies between these two areas of disturbance on the north and the Llano-Burnet uplift on the south, and its structural features are greatly influenced by its position with regard to them. The areal and structural geology of the region is shown in generalized form on Plates II and III.

The oil-bearing rocks of the north Texas region are of Carboniferous age, and Carboniferous formations also constitute the surface rocks throughout most of the region. Pre-Carboniferous beds do not crop out within the helium-bearing area and have not been penetrated by the drill except in its southern portion, but they may be studied in the Llano-Burnet uplift, to the south, and in the Wichita and Arbuckle mountains, to the north. The



ENGRAVED AND PRINTED BY THE U. S. GEOLOGICAL SURVEY

MAP OF NORTHERN TEXAS AND SOUTHERN OKLAHOMA

Showing oil and gas fields, distribution of helium-bearing gas, and relations of fields to area of uplift

Scale $\frac{1}{2500000}$

10 0 20 40 60 MILES

1920

formations involved are shown in the accompanying columnar section (fig. 4), in which the data regarding the pre-Carboniferous formations are based on observations in the Llano-Burnet district.

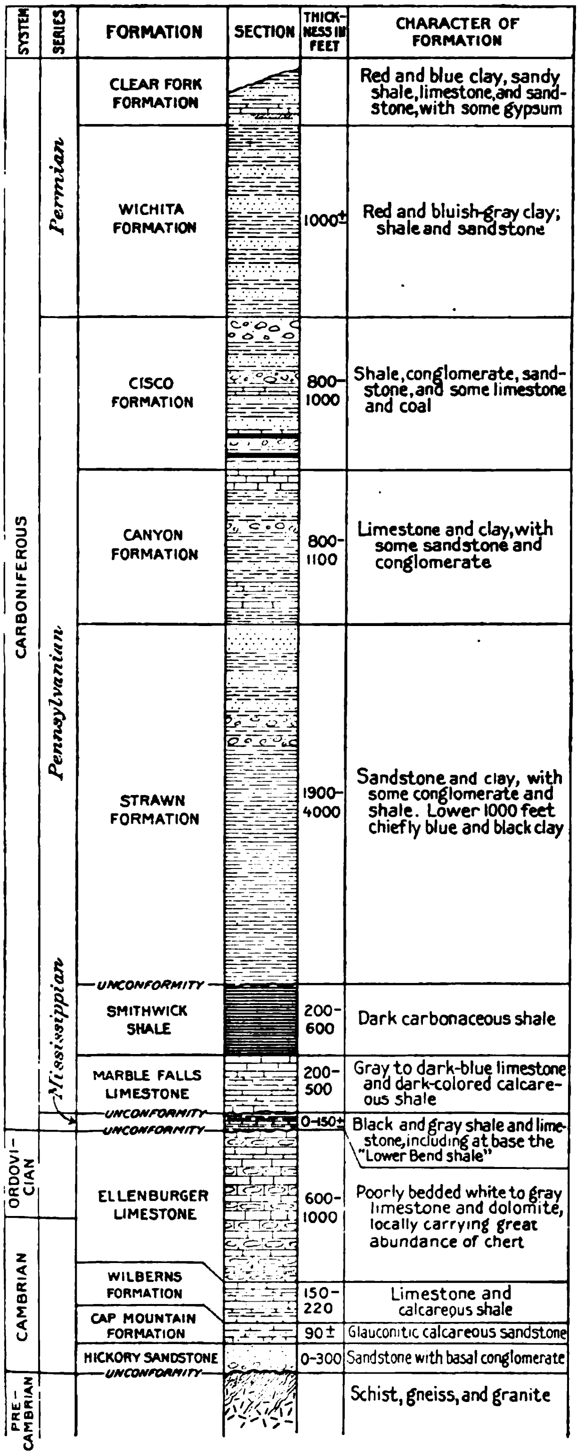

SYSTEM
SERIES
FORMATION
SECTION
THICKNESS IN FEET
CHARACTER OF FORMATION
CARBONIFEROUS
Permian
CLEAR FORK FORMATION
Red and blue clay, sandy shale, limestone, and sandstone, with some gypsum
WICHITA FORMATION
1000±
Red and bluish-gray clay; shale and sandstone
Pennsylvanian
CISCO FORMATION
800-1000
Shale, conglomerate, sandstone, and some limestone and coal
CANYON FORMATION
800-1100
Limestone and clay, with some sandstone and conglomerate
STRAWN FORMATION
1900-4000
Sandstone and clay, with some conglomerate and shale. Lower 1000 feet chiefly blue and black clay
Mississippian
UNCONFORMITY
SMITHWICK SHALE
200-600
Dark carbonaceous shale
MARBLE FALLS LIMESTONE
200-500
Gray to dark-blue limestone and dark-colored calcareous shale
UNCONFORMITY
0-150±
Black and gray shale and limestone, including at base the "Lower Bend shale"
UNCONFORMITY
ORDOVICIAN
ELLENBURGER LIMESTONE
600-1000
Poorly bedded white to gray limestone and dolomite, locally carrying great abundance of chert
CAMBRIAN
WILBERNS FORMATION
150-220
Limestone and calcareous shale
CAP MOUNTAIN FORMATION
90±
Glauconitic calcareous sandstone
HICKORY SANDSTONE
0-300
Sandstone with basal conglomerate
UNCONFORMITY
PRE-CAMBRIAN
Schist, gneiss, and granite

Figure 4.—Generalized columnar section of formations in north-central Texas. The thicknesses of the pre-Carboniferous formations are those measured by Paige in the Llano-Burnet uplift. The equivalent formations in the Wichita and Arbuckle uplifts are very much thicker; hence in the north Texas oil region they are doubtless considerably thicker than here shown.

The formations exposed in the Llano-Burnet area have been described in detail by Paige.[33] The oldest rocks are granite, schist, and gneiss, with igneous intrusions, and are probably of Algonkian age. These rocks are surrounded by a rim of Cambrian and Ordovician beds dipping outward from the center of the uplift. As shown in the columnar section these rocks consist chiefly of limestone, dolomite, and calcareous sandstone and shale, with a conglomerate at the base, and aggregate 950 to 1,600 feet in thickness. In the Wichita Mountains, however, the pre-Pennsylvanian formations, according to Taff,[34] have a very much greater thickness. The earliest Cambrian formation in the Wichita Mountains is similar in character and thickness to the Hickory sandstone of Texas, but it is overlain by a Cambrian and Ordovician formation, the Arbuckle limestone, which is 4,000 to 6,000 feet thick. The only other pre-Carboniferous formation exposed in the Wichita Mountains is an Ordovician limestone about 300 feet thick, but in the Arbuckle Mountains, 60 miles to the east the formations present include the Simpson formation and the Viola limestone of Ordovician age, aggregating 2,000 to 2,500 feet in thickness; the Sylvan shale, also of Ordovician age, 60 to 300 feet thick; the Chimneyhill limestone, 53 feet thick, and the Henryhouse shale, 223 feet thick, of Silurian age; the Haragan shale, 161 feet thick, the Bois d'Arc limestone, 90 feet thick, and the Woodford chert, about 650 feet thick, all of Devonian age.

The aggregate thickness of pre-Carboniferous formations in the Arbuckle Mountains is 6,900 to 10,250 feet, and although in the Wichita Mountains only 4,500 to 6,600 feet of pre-Carboniferous rocks are exposed, it is possible that several thousand feet more of these beds are present but are concealed by the mantle of Permian formations that unconformably overlies them. Whether this is so or not, however, it is evident that the pre-Carboniferous beds are very much thicker in southern Oklahoma than in the Llano-Burnet area in central Texas, where they have a maximum thickness of only 1,600 feet. Beneath the northern part of the helium-bearing district, therefore, these formations are probably from 3,000 to 6,000 feet thick, unless, as in Kansas, there are irregularities in the pre-Cambrian floor that cut out some of the basal beds. This possibility is disregarded in the representation of the structure of the pre-Carboniferous rocks and their thickening to the north in the structure section on Plate II.

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[33] Paige, Sidney, U. S. Geol. Survey Geol. Atlas, Llano-Burnet folio (No. 183), 1912.

[34] Taff, J. A., Preliminary report on the geology of the Arbuckle and Wichita mountains, in Indian Territory and Oklahoma: U. S. Geol. Survey Prof. Paper 31, 1904.

The Cambrian and Ordovician limestone in the Llano-Burnet area is unconformably overlain by the Marble Falls limestone, of Pennsylvanian age. Just north of that area, however, the Marble Falls is separated from the Ordovician by limestone and shales believed to be of upper Mississippian age. The lower part of these Mississippian beds has been called "Lower Bend shale."[35] The Marble Falls limestone is overlain by the Smithwick shale, and the Smithwick is unconformably overlain by the Strawn formation. Because of the unconformities at the base of the so-called "Lower Bend shale," at the base of the Marble Falls, and at the top of the Smithwick, the combined thickness of these formations varies considerably, though in general it increases somewhat toward the north. On the outcrop, where the Mississippian is absent, the Smithwick and Marble Falls together are 550 to 850 feet thick, but in the Ranger district the combined thickness of the three formations is almost 1,000 feet.[36] The highly prolific oil sands encountered at depths of 3,000 to 3,500 feet in the Ranger, Breckenridge, Caddo, and neighboring pools occur in the "Bend series," mainly in the Marble Falls limestone, and chiefly in its upper portion, and one or two wells have also found oil and gas in the overlying Smithwick shale.

The Smithwick shale is overlain by the Strawn, Canyon, and Cisco formations, of Pennsylvanian age, which consist chiefly of sandstone and shale with some coal. Cummins,[37] Drake,[38] Hill,[39] and others have shown that the Strawn formation is about 2,500 feet thick in the neighborhood of Strawn, Palo Pinto County, and in some places reaches a thickness of 4,000 feet. Its thickness in north Texas, however, as measured by Gordon,[40] is only 1,900 feet. The Strawn consists chiefly of blue to black shale and reddish sandstone. It includes several workable coal beds and the oil sands that are productive chiefly in Palo Pinto County. The Strawn is overlain by the Canyon formation, which is 800 to 1,100 feet thick and which consists chiefly of shale and limestone in the Ranger region but becomes more sandy toward the north. Matteson[41] has called attention to the pronounced unconformity between the Strawn and Canyon formations in the Ranger region and in north-central Texas generally. The Canyon is overlain by the Cisco formation, which is 800 to 1,000 feet thick and which consists chiefly of red to blue shale and reddish sandstone. The helium-bearing gas of the Petrolia field and much of the oil of the Electra and Burkburnett fields probably occur in the Cisco formation.

In northern and central Texas sedimentation was not interrupted at the end of the Pennsylvanian epoch, and the great series of Permian beds rests conformably on the Pennsylvanian strata. The lowest Permian formation, the Wichita, is lithologically very similar to the Cisco formation and yields the shallow oil of the Petrolia, Electra, and Burkburnett fields. The Wichita, which is 1,000 to 1,200 feet thick, is overlain by the Clear Fork and Double Mountain formations, which have a combined thickness of almost 4,000 feet, but these beds crop out west of the area under discussion and need not be considered here.

The conditions of sedimentation in southern Oklahoma differed from those in Texas in several particulars. As already noted, the thickness of the pre-Carboniferous formations in southern Oklahoma is very much greater than in Texas, and in the Arbuckle Mountains, at least, sedimentation continued without notable interruption through Mississippian time. At the end of the Mississippian, however, the Arbuckle region was uplifted into land, and so it remained during a great part of Pennsylvanian time. During this epoch only a comparatively small thickness of strata was deposited in the Arbuckle region proper, though in central and northern Texas the thick series of beds represented by the Marble Falls, Smithwick, Strawn, Canyon, and Cisco formations was laid down. Moreover, near the end of the Pennsylvanian the sediments of the Arbuckle region were again folded and elevated into land, and a great hiatus occurred between the deposition of the highest Pennsylvanian formations and that of the lowest Permian. During the same period sedimentation in north Texas, resulting in the formation of the Wichita and Cisco beds, was practically continuous; hence in southern Oklahoma part or all of the Wichita and Cisco and perhaps still lower beds are absent. The exact conditions can not be determined, except in the immediate vicinity of the Arbuckle uplift, for elsewhere all the older rocks are unconformably overlain by a blanket of Permian beds; hence at present it is impossible to correlate the oil and gas zones of southern Oklahoma with those of northern Texas.

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[35] Udden, J. S., Review of geology of Texas: Texas Univ. Bull. 44, pp. 41, 42, 1916.

[36] Matteson, W. G., A review of development in the new central Texas oil fields during 1918: Econ. Geology, vol. 14, p. 95, 1919.

[37] Cummins, W. F., Texas Geol. Survey Second Ann. Rept., 1891.

[38] Drake, N. F., Texas Geol. Survey Fourth Ann. Rept., 1893.

[39] Hill, R. T., U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, 1901.

[40] Gordon, C. H., Geology and underground waters of the Wichita region, north-central Texas: U. S. Geol. Survey Water-Supply Paper 317, p. 14, 1913.

[41] Matteson, W. G., Econ. Geology, vol. 14, p. 105, 1919.

That the tectonic relations of the north Texas region are complex and difficult to decipher is clear from the foregoing discussion. It is evident that the pre-Carboniferous rocks form a sort of basin between the Llano-Burnet uplift on the south and the Wichita and Arbuckle uplifts on the north. Although there is no marked discordance in dip in the Llano-Burnet region between these formations and the Carboniferous, farther north the upper surface of the pre-Carboniferous is very irregular and its structure may be very different from that of the Carboniferous formations. In the Llano-Burnet district the lower Pennsylvanian beds have a general northerly dip, and in the Ranger region they are known to dip also to the east and west, forming a broad, gentle anticline whose northward-plunging axis is a radial extension of the Llano-Burnet uplift. The Strawn and higher formations dip in general to the northwest, their structure being controlled in part by the Llano-Burnet uplift and in part by their position on the eastern rim of the great Carboniferous basin of west Texas. The Permian beds in Texas are conformable to the Pennsylvanian, but in southern Oklahoma they are unconformable and conceal the complicated structure which undoubtedly characterizes all the older formations in that area.

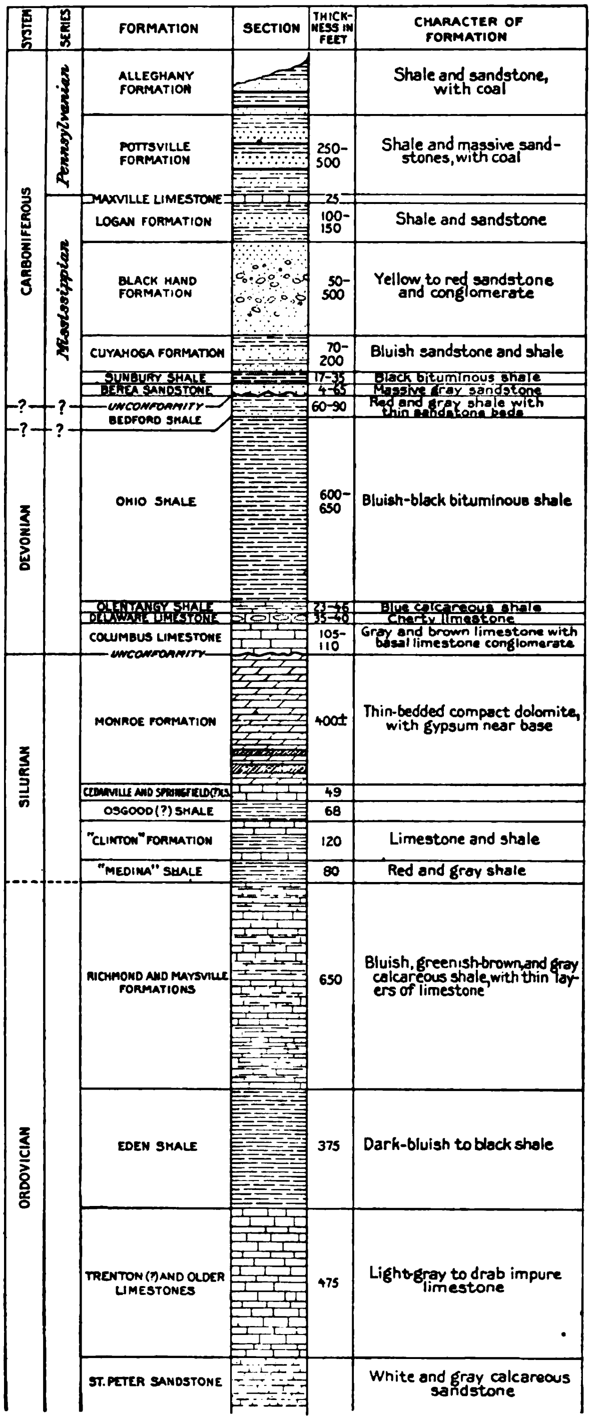
DISTRIBUTION OF THE HELIUM.

The gas produced in all the fields of northern and central Texas and southern Oklahoma has been tested for helium, and the results are shown on Plate III. It will be noted that the only field producing gas carrying more than 0.5 per cent of helium is Petrolia, that gas carrying more than 0.25 per cent is found throughout a large area south of Petrolia, and that all the southern Oklahoma fields yield gas very poor in helium. As the fields in this region are fewer than those in the Mid-Continent region and are also more widely separated, it is even more difficult to draw definite conclusions as to the factors covering the distribution of the helium, though its broader stratigraphic relations are plain. The rich Petrolia gas occurs in the upper Pennsylvanian, and the poorer gases to the south in the lower Pennsylvanian. The Permian gases of southern Oklahoma and the basal Pennsylvanian and Mississippian gases of the Ranger region are poor in helium, and the Cretaceous gases of east-central Texas and Louisiana contain only traces of helium or none at all. The stratigraphic distribution of the helium in this region is thus similar to that in the Mid-Continent district; the richest gases are of upper and middle Pennsylvanian age, and both older and younger gases are poor.

The Petrolia gas, which carries almost 1 per cent of helium, is derived from a zone of sands that lies at a depth of 1,500 to 1,750 feet and is believed to occur in the Cisco formation. The gas sands are lenticular and can not be traced for any great distance, but there appear to be two main producing groups of sands, one lying at an average depth of about 1,550 feet and the other at about 1,700 feet. A less definite zone occurs between the two, and "stray" sands are also reported in many wells. Samples collected from individual wells show a range in helium from 0.65 to 1.18 per cent, and the gas from the uppermost group of sands is apparently slightly richer than that from the others. As all these groups, however, lie in one general zone, and as no gas is produced from other zones in the field, it is impossible to determine how far the helium content of the gas is related to its depth or its exact stratigraphic position.

The Petrolia field is the only locality in which gas is produced from sands that are almost certainly in the Cisco formation. In the Electra and Burkburnett fields, a short distance west of Petrolia, oil is obtained from sands in the Cisco and in the overlying Permian, but no commercial supplies of gas have been found.

the east and southeast. The general geology of the region is well brought out in figure 5. The highest part of the broad, gentle Cincinnati anticline is defined by the outcrop of Ordovician rocks, and this is surrounded by the Silurian, Devonian, Mississippian, and Pennsylvanian strata that are exposed farther down on the flanks of the anticline. The area in which Permian formations constitute the surface rocks marks the deepest part of the basin, and east of this locality the general dip of the strata is west and northwest. The dip increases sharply in the mountains, where the Mississippian and older Paleozoic formations, thrown into a series of closely compressed folds, are again exposed. Pre-Cambrian rocks crop out still farther east, in the extreme southeast corner of the area mapped.



SYSTEM	SERIES	FORMATION	SECTION	THICKNESS IN FEET	CHARACTER OF FORMATION
CARBONIFEROUS	*Pennsylvanian*	ALLEGHANY FORMATION			Shale and sandstone, with coal
		POTTSVILLE FORMATION		250-500	Shale and massive sandstones, with coal
	Mississippian	MAXVILLE LIMESTONE		25	
		LOGAN FORMATION		100-150	Shale and sandstone
		BLACK HAND FORMATION		50-500	Yellow to red sandstone and conglomerate
		CUYAHOGA FORMATION		70-200	Bluish sandstone and shale
		SUNBURY SHALE		17-35	Black bituminous shale
		BEREA SANDSTONE		4-65	Massive gray sandstone
?	?	*UNCONFORMITY*			
		BEDFORD SHALE		60-90	Red and gray shale with thin sandstone beds
?	?				
DEVONIAN		OHIO SHALE		600-650	Bluish-black bituminous shale
		OLENTANGY SHALE		23-46	Blue calcareous shale
		DELAWARE LIMESTONE		35-40	Cherty limestone
		COLUMBUS LIMESTONE		105-110	Gray and brown limestone with basal limestone conglomerate
		UNCONFORMITY			
SILURIAN		MONROE FORMATION		400±	Thin-bedded compact dolomite, with gypsum near base
		CEDARVILLE AND SPRINGFIELD(?)LS.		49	
		OSGOOD (?) SHALE		68	
		"CLINTON" FORMATION		120	Limestone and shale
		"MEDINA" SHALE		80	Red and gray shale
ORDOVICIAN		RICHMOND AND MAYSVILLE FORMATIONS		650	Bluish, greenish-brown, and gray calcareous shale, with thin layers of limestone
		EDEN SHALE		375	Dark-bluish to black shale
		TRENTON (?) AND OLDER LIMESTONES		475	Light-gray to drab impure limestone
		ST. PETER SANDSTONE			White and gray calcareous sandstone

FIGURE 6.—Columnar section of rocks exposed and encountered in drilling in south-central Ohio. Based on data given by Phalen, W. C., U. S. Geol. Survey Geol. Atlas, Kenova folio (No. 184), 1913, and by Hubbard, G. D., Stauffer, C. R., Bownocker, J. A., Prosser, C. S., and Cumings, E. R., idem, Columbus folio (No. 197), 1915.

The formations exposed and encountered in drilling in the Vinton County area range in age from Pennsylvanian to Ordovician, as shown in the columnar section (fig. 6). The surface formations are the Allegheny and Pottsville, of lower Pennsylvanian age, which consist of shale and sandstone with numerous coal beds. In Ohio the top of the Mississippian is marked by a thin limestone, but the series consists chiefly of shale and sandstone formations having an aggregate thickness of about 300 to 800 feet. The Berea sandstone, which lies at or near the base of the Mississippian, is an important reservoir of oil and gas throughout the Appalachian region. The upper and middle parts of the underlying Devonian system consist chiefly of dark shale, but the lower part is composed of two limestone formations. In the Columbus area, about 60 miles north of Vinton County, the Devonian has an aggregate thickness of 825 to 915 feet. The upper part of the Silurian system consists of limestone and dolomite formations about 450 feet thick, and the lower part, about 270 feet thick, is represented by a shale supposed to be the Osgood shale, the "Clinton" formation, and an underlying shale that represents a part of the Medina group.

The "Clinton" formation[45] is of special interest because it includes the Clinton sand, the chief reservoir of natural gas in central Ohio and of helium-bearing gas in the Vinton County field. The "Clinton" formation crops out on the east flank of the Cincinnati anticline west of Vinton County and, dipping to the east, attains a depth of 2,000 to 2,600 feet in the Vinton County field. East of that locality the depth of the "Clinton" increases sharply, owing not only to the normal dip but to the great thickening of the Devonian shale above it, and in western Pennsylvania and West Virginia the formation lies at depths greater than 7,000 feet. The Clinton sand itself does not appear in the surface exposures of the "Clinton" formation, and drill records indicate that it feathers out and merges into shale along the western edges of the Vinton County field and of the other Clinton sand fields to the north. This thinning out of the sand has undoubtedly been the chief factor in the accumulation of natural gas throughout the belt, and most of the Clinton sand fields have monoclinal rather than true anticlinal structure.

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[45] When gas was first discovered in these rocks at Lancaster the formation was thought to be the equivalent of the Clinton of New York. Later studies have shown that the beds lie below the true Clinton and probably belong to the Medina group. As the term Clinton sand is now too well established among the drillers to be supplanted, and as no other name for the formation that contains this sand has yet been generally accepted, the term "Clinton" formation is retained in this paper in conformity with current usage.

No wells in the Vinton County district have penetrated far below the Clinton sand, but the records of deep wells near Columbus and near Waverly furnish information as to the character and thickness of the Ordovician rocks. As shown in figure 6, the data for the lower part of which are derived from the record of a well near Columbus, the "Clinton" is underlain by more than 1,800 feet of Ordovician beds. The upper 1,000 feet of the Ordovician consists chiefly of shale, at the base of which lies 475 feet of limestone, which has been classified as Trenton (?) and older.

This is underlain by 316 feet of white sandstone that is believed to represent the St. Peter. The record of the well at Waverly, however, which is only 20 miles west of the Vinton County area, shows only 175 feet of sandstone at the horizon of the St. Peter and 320 feet of white dolomitic limestone below. According to Bassler's interpretation [46] of this record, the white limestone is of Lower Ordovician age. Drillings obtained near the bottom of this well included a few fragments of a basic igneous rock which Bassler regards as probably representing the pre-Cambrian basement. If this view is correct the Clinton sand at Waverly is underlain by about 2,500 feet of sedimentary rocks, and in Vinton County the thickness of pre-"Clinton" sediments is presumably about the same.

The only known outcrop of igneous rock in this region is near Willard, Ky., about 85 miles south of Vinton County. The rock is kimberlite, a variety of peridotite, and appears to represent a dike that was intruded in post-Allegheny time.

DISTRIBUTION OF THE HELIUM.

The occurrence of helium in the Vinton County area was investigated by George B. Richardson, of the Geological Survey, from whose reports the following information has been taken. (See p. 90).

By far the largest supply of helium-bearing gas is found in the Clinton sand, which ranges in depth from about 2,050 to 2,450 feet and dips to the east at a fairly regular rate of 60 to 70 feet to the mile. In the eastern part of the field the sand is 20 feet or more thick, but it thins toward the west and feathers out in the western part of the county. The Clinton gas carries from 0.20 to 0.48 per cent of helium, though 14 out of the 18 samples collected showed between 0.34 and 0.44 per cent. The slight variation in helium content appears to be irregular, and no evidence of segregation, either geographic, stratigraphic, or structural, could be detected. Samples collected on the east side of the field showed as much helium as those on the west side, where the sand lies 350 feet higher.

A fact of considerable scientific interest is the occurrence of natural gas carrying practically the same proportion of helium—0.39 per cent—in a sand at or near the horizon of the Berea, which lies about 1,850 feet stratigraphically above the Clinton sand. As pointed out in the foregoing pages, in the Mid-Continent region the gas richest in helium occurs characteristically at shallow depth, and in both the Mid-Continent and the north Texas fields the distribution of the helium-rich gases is distinctly related to the stratigraphy. The fact that the Clinton gas of Vinton County carries as much helium as the Berea gas, which is far younger and which occurs relatively close to the surface, is therefore surprising. The occurrence of helium in the Berea gas is of little practical importance in Vinton County, however, for the production from this sand is small, whereas that from the Clinton amounts to about 65,000,000 cubic feet a day.

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[46] Bassler, R. S., Stratigraphy of a deep well at Waverly, Ohio: Am. Jour. Sci., 4th ser., vol. 31, p. 19, 1911.

ROCKY MOUNTAIN AND PACIFIC COAST REGIONS.

During the summer of 1918 practically all commercial supplies of natural gas in Wyoming, the Dakotas, Montana, Washington, and California were sampled, the Wyoming samples being collected by C. A. Fisher, consulting geologist, of Denver, Colo., and the remainder by A. W. Ambrose and E. W. Wagy, of the Bureau of Mines. The gas at Havre, Mont., proved to contain 0.27 per cent of helium; that at Pine Mountain, Wyo., about 0.26 per cent; and that at Fillmore, Calif., 0.31 per cent; but none of the other gases sampled contained more than 0.15 per cent, and the great majority contained only traces of helium or none at all. With the exception of the gas from Pine Mountain, Wyo., which is derived from a Carboniferous formation, practically all the gas produced in the Rocky Mountain and Pacific coast region is of Cretaceous or Tertiary age. This fact, taken in connection with the very low helium content of the Cretaceous and Tertiary gases of Texas and Louisiana, indicates that the prospects of discovering helium-rich gas in Cretaceous and Tertiary strata are poor.

The small Havre gas field in north-central Montana is in the southeastern part of Hill County and lies only about 30 miles south of the international boundary. The sample of Havre gas analyzed was collected from a well at the west end of the town and is presumably representative of the gas produced by the two or three other wells that have been drilled in the vicinity. The gas analyzed occurs at a depth of 1,200 to 1,300 feet, and according to Stebinger[47] it is derived from the Eagle sandstone, which is the basal formation of the Montana group, of Upper Cretaceous age. The predominant surface rock in the vicinity of Havre is the Judith River formation, one of the higher formations in the same group. The Eagle is underlain by the Colorado shale, 1,500 to 1,700 feet thick, and the Colorado in turn by the Kootenai formation, of Lower Cretaceous age, 400 to 600 feet thick. On the east flank of the Bearpaw Mountains, about 30 miles southeast of Havre, the Kootenai is underlain by older Mesozoic and Paleozoic formations, but owing to the disturbed condition of the strata in this region it is impossible to determine the thickness of the sediments which in the Havre district separate the Eagle sandstone from the basement rocks. The north end of the main igneous mass of the Bearpaw Mountains lies only about 10 miles south of Havre, and small isolated exposures of intrusive rock appear within 2 or 3 miles of the gas wells.

Considerable volumes of natural gas are produced in Canada, and during the war the helium content of Canadian gases was investigated. No report of this investigation has been published, but it is understood that no gases containing more than about 0.33 per cent of helium were discovered.

The gas produced in the Pine Mountain dome, 25 miles northwest of Casper, in central Wyoming, is derived from a Carboniferous formation. According to Hares[48] the producing formation is probably the Tensleep sandstone, of Pennsylvanian age, though C. A. Fisher, who collected the samples, states that the gas may be derived from the overlying Embar group, which is of Pennsylvanian, Permian, and Lower Triassic age. The gas occurs at a depth of 1,668 feet. Unfortunately, the sample was lost during analysis, and the helium content was not exactly determined, but C. W. Seibel, who made the analysis, regards 0.26 per cent as a close approximation.

The most interesting feature of the Pine Mountain gas is the fact that it contains more than twice as much helium as any of the other Wyoming gases tested, all of which are of Cretaceous age. A sample from the Frontier sand (Colorado group of Upper Cretaceous age), in the Buffalo Basin field, showed 0.07 per cent, and a sample from the Cloverly formation (Lower Cretaceous), in the Oregon Basin field, showed 0.09 per cent. Nine samples from these and other Cretaceous beds contained only a trace of helium, and three samples contained none. Hence, in Wyoming, as in the Mid-Continent region, the gas richest in helium appears to be of Carboniferous age.

The shallow gas at Fillmore, Ventura County, Calif., is remarkable as the only one of the 56 California gases sampled that contains more than 0.15 per cent of helium. This gas, which contains 0.31 per cent of helium, occurs at a depth of about 600 feet, and according to Eldridge[49] it is probably derived from the Sespe formation, of Oligocene(?) age. A sample from a more productive gas sand in the same field, lying at an average depth of 2,800 feet, showed, however, only 0.06 per cent of helium. A sample from the Santa Maria field, also in southern California, contained 0.13 per cent of helium, and one from the Coalinga field in Fresno County contained 0.11 per cent, but the remaining 51 samples collected from these and other fields contained only traces of helium at the most. (See pp. 96–97.)

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[47] Stebinger, Eugene, Possibilities of oil and gas in north-central Montana: U. S. Geol. Survey Bull. 641, pp. 49-92, 1917.

[48] Hares, C. J., Anticlines in central Wyoming: U. S. Geol. Survey Bull. 641, pp. 233-280, 1917.

CANADA.

A sample of the gas produced in the Bow Island field, near Lethbridge, Alberta, about 125 miles northwest of Havre, Mont., was collected in August, 1918, by A. W. Ambrose and was found to contain 0.30 per cent of helium. At that time there were 26 gas wells in the Bow Island field having an average depth of 1,900 feet and a combined open flow of 15,000,000 cubic feet a day. This gas is supposed to occur in the lower part of the Colorado shale, or about 1,200 to 1,500 feet below the producing sand at Havre. The fact that both these gases carry about the same proportion of helium suggests that similar gas may be found elsewhere in this region in Cretaceous formations.

EUROPE.

Systematic searches for helium-bearing natural gas in European countries were not made until after the outbreak of the European war, and the results of these explorations have not been published. Prior to the discovery of helium in Kansas natural gas by Cady and McFarland, however, a number of Italian gases of various types had been tested by Nasini, Anderlini, and Salvadori,[50] and faint traces of helium had been detected in the natural gas of Bagni della Porretta, on the northern flank of the Apennines. (See p. 51.) The same investigators in 1906 identified helium in the natural gas of Salsomaggiore,[51] in northern Italy, and since that time the helium in a number of other European gases has been quantitatively determined by several chemists. Unfortunately the memoirs in which these analyses were published give little information as to the geologic occurrence of the gases, but the data given have some interest in connection with the foregoing discussion of the occurrence of helium in North American gases.

Helium was found in the gas produced at Neuengamme, near Hamburg, by Voller and Walter[52] in 1910. They found this gas, which occurs in Tertiary strata at a depth of 810 feet, to contain 5.6 per cent of nitrogen, 0.05 per cent of argon, and 0.01 to 0.02 per cent of helium. A later analysis of the same gas by Czakó[53] showed 3.32 per cent of nitrogen and 0.0141 per cent of helium, and a test by Sieveking and Lautenschläger[54] showed 0.025 per cent of helium. The last-named authors also examined gas from Transylvania, the most productive gas region in Europe, and found it to contain 0.007 per cent of helium. Gas from Kissármás, in the same region, was found by Czakó to carry 0.0014 per cent of helium. Czakó found less than 0.01 per cent of helium in the gas produced at Wels, Austria, and in the shallow gas of the Alsatian field but reported 0.38 per cent in a small flow of gas from a deep test hole near Pechelbronn, Alsace. This gas is derived from a depth of about 3,280 feet, and the occurrence of a gas comparatively rich in helium at so great a depth is somewhat surprising in view of the apparent tendency of helium in the North American fields to collect at shallow depth. All the other European gases analyzed are believed to be of Tertiary age, however, whereas the deep Pechelbronn gas is said to issue from the Urformation, which in this locality is presumably of early Mesozoic age.

Czakó determined the radioactivity of the gases which he tested for helium and found the deep Pechelbronn gas to be very much more active than the gases poor in helium. He also examined a number of other natural gases for radioactivity and found them to be about as active as the gases known to contain only very small amounts of helium. His results are given in the following table:

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[49] Eldridge, G. H., and Arnold, Ralph, The Santa Clara Valley, Puente Hills, and Los Angeles oil districts, southern California: U. S. Geol. Survey Bull. 300, p. 76, 1907.

[50] Nasini, R., Anderlini, F., and Salvadori, R., Ricerche sulle emanazioni terrestre italiane: Gazz. chim. ital., vol. 28, pp. 81-153, 1898.

[51] Idem, vol. 36, pt. 1, p. 429, 1906.

[52] Voller, A., and Walter, B., Über den Helium und Argongehalt des Erdgases von Neuengamme: Hamburgischen wissenschaftlichen Anstalten Jahrb., Band 28, Heft 5, 1910.

[53] Czakó, Emerich, Über Heliumgehalt und Radioaktivität von Erdgasen: Zeitschr. anorg. Chemie, vol. 82, pp. 261, 268, 1913; Beiträge zur Kenntnis naturlicher Gasausströmungen, Dissertation, Grossherzoglich technischen Hochschule zu Karlsruhe, 1913.

[54] Sieveking, H., and Lautenschläger, L., Über Helium in Thermalquellen und Erdgasen: Physikal. Zeitschr., vol. 13, p. 1043, 1912.

Helium content and radioactivity of some European natural gases.

Source.	Depth of well (feet).	Flow of gas per day (thousand cubic feet).	Radioactivity (volt-stunden).	Helium (per cent).	Nitrogen (per cent).	Date sampled.
Neuengamme, near Hamburg, Germany	810	17,657±	580	0.0141	3.32	December, 1911.
Wels, upper Austria:						
Scharf well	1,246		165	.0089		September, 1912.
Krankenhaus well	820-1,312		290			Do.
Herdfabrik well	590-754	39±	700			Do.
Pechelbronn, Alsace:						
Well 220	901		300	.0063	6.36	April, 1912.
Well 1261	469		300			Do.
Old well			500			Do.
Deep well	3,280±		17,000	.38	46.55	Do.
Kissármás, Hungary:						
Well II	990	30,371	70	.0014	.73	September, 1912.
Well XII	738	7,240	50			Do.
Well XIII	354	2,472	120			Do.
Well X	223	1,942	85			Do.
Bázna, Hungary, well XIV	459	1,942	125			Do.
Medgzes, Hungary, well XXII	335	635	140			Do.
Marosugra, Hungary, well V	4,165	127±	280			Do.
Campina, Rumania, well 103	1,580		110			Do.

All the European natural gases that have been tested are therefore very poor in helium with the exception of the small flow from the deep well at Pechelbronn; and if, as Czakó apparently believes, the radioactivity of a gas is a rough index of its helium content it is evident that all the other gases cited in the foregoing table are also poor in helium. As already pointed out, the Tertiary and Cretaceous gases of the United States are, with two exceptions, very poor in helium, and as practically all the European natural gases are of Tertiary age their low helium content is not surprising. It would of course be unwise to infer that all Cretaceous and Tertiary gases the world over are poor in helium, though this conclusion is suggested both by the scanty available evidence relating to helium in European gases, and by the abundant evidence regarding the distribution of helium in the United States.

SUMMARY OF FACTORS INFLUENCING THE DISTRIBUTION OF HELIUM.

In the foregoing pages the writer has endeavored to describe broadly the geologic occurrence of helium-bearing natural gas and to point out the factors that seem to influence its distribution in different regions. At the present time only general conclusions can be drawn, however, for two neighboring wells producing from the same horizon may yield gases differing in helium content, and until the cause of such local variations is understood it is unwise to attach much significance to small differences in the helium content of gases produced in widely separated fields.

In the Mid-Continent region, which contains the largest known accumulations of helium-bearing gas, the richest gas occurs at comparatively shallow depths in upper and middle Pennsylvanian strata. In the Texas region, which is the next most prolific, the stratigraphic distribution of the gas is the same, and there is reason to believe also that rich gas will not be found at great depth. In Ohio, however, a large volume of gas carrying 0.33 per cent of helium is found in Silurian strata at a depth of more than 2,000 feet, and a small volume of equally rich gas occurs in Mississippian beds about 1,800 feet stratigraphically higher. Gas of Cretaceous and Tertiary age is usually very poor in helium, though in two localities such gas has been found to contain slightly more than 0.25 per cent.

As the helium-bearing gas in the Mid-Continent and Texas regions has a definite stratigraphic distribution, the boundaries of the helium-rich areas are to some extent determined by the structural and areal geology. In large part, however, these boundaries appear to be controlled by some local conditions which are not yet understood and which can be determined, if at all, only by special study. It is possible that the sediments in the helium-bearing areas are peculiar in composition, perhaps containing disseminated deposits of the radioactive minerals that generate helium. Or, it is possible that unusual structural conditions characterize the rocks beneath the helium-bearing areas and that the helium has ascended from deep-seated sources and mingled with the hydrocarbon gases formed above.

The belief that the helium is of plutonic origin is a popular one, and the writer has frequently been asked whether it is not possible to account for the helium as having arisen through fissures from great depths. Some warrant for this belief is afforded by the buried granite ridge on the west edge of the Mid-Continent region, which, as already described, was probably formed in part by faulting. Inasmuch, however, as the ridge extends far to the north of the helium-bearing area and probably also to the south of it, and as helium is found also many miles east of the ridge, little weight can be attached to this evidence. The practical absence of helium in the deep gases nearer the granite is a strong argument against the supposition that the helium has risen from deep-seated sources; and furthermore, there is no evidence in either the north Texas or the Ohio districts for supposing that there are any similarly unusual structural features in the basement rocks.

On the other hand, there is some evidence directly opposed to the view that helium has arisen along fissures, for the gas produced in most fields that are close to areas of uplift or to igneous intrusions is poor in helium. For example, as shown on Plate III, the fields of southern Oklahoma, which are close to the Wichita and Arbuckle uplifts, yield gas very poor in helium; and several of the Wyoming fields, which are not far from areas of uplift and intrusion, produce gas carrying only traces. The Havre field is, in fact, the only district close to an uplift which is known to produce gas carrying more than 0.25 per cent of helium. Moreover, gas produced from a depth of 730 feet beneath a Tertiary lava flow near Prosser, Wash., contains only 0.06 per cent of helium, and the gas of the Thrall field, Texas, which issues directly from a body of serpentine, contains no helium at all. The observed occurrences of the helium-bearing gas thus afford little basis for supposing that the helium is associated with unusual structure or with igneous activity.

CHEMICAL COMPOSITION OF HELIUM-BEARING NATURAL GAS.

CONSTITUENTS OF NATURAL GAS.

Although all gaseous mixtures that issue from the earth are of course natural gases, the term natural gas is ordinarily restricted to the gaseous mixtures rich in hydrocarbons that are generally associated in nature with petroleum. In many of the old analyses of natural gas a great variety of constituents are reported, but recent improvements in the technique of gas analysis indicate that the constituents are comparatively few in number and that natural gas is sufficiently uniform in character to warrant its recognition as a chemically distinct type. Many varieties are known, however, and between them all gradations exist.

The characteristic and principal constituents of ordinary natural gas are the light paraffin hydrocarbons, methane and ethane, with generally smaller proportions of propane and the next higher members of the paraffin series. "Dry" gas not directly associated with petroleum usually consists chiefly of methane with a little ethane; "wet" gas occurring in the same sand with oil may carry also propane, butane, pentane, and hexane. The composition of gas occurring directly with oil is, however, influenced by the decrease in pressure due to the removal of oil and gas from the sands; in the early stages of a field's life such a gas may consist chiefly of methane and ethane, but as the pressure decreases the heavier hydrocarbons, previously dissolved in the oil, are released, and the gas may then consist chiefly of propane and butane. Such gases are valuable on account of their heavier hydrocarbons, which may be extracted and condensed as gasoline; but they occur only in association with oil, and their total volume is small in comparison with that of the high-methane gases that are chiefly used for heating and lighting. Owing to the fact that the composition of "wet" or casing-head gas is largely a function of the pressure in the sand, such gases are not likely to carry helium in proportions large enough to be of value. Most of the gases sampled during the present investigation were therefore "dry" gases occurring in sands that do not yield oil.

Analyses made by the ordinary or eudiometric method do not show the higher hydrocarbons, which can be separated only by fractional distillation at low temperatures.[55] In the ordinary method of analysis the hydrocarbons are treated as a unit and the results are expressed, by algebraic calculation, in terms of methane and ethane alone. Nevertheless, the work of Burrell and his associates indicates that small proportions of propane and butane are present in many or most gases, though, on the other hand, it shows also that the olefin hydrocarbons which are reported in many old analyses probably do not occur in any natural gas.[56]

Analyses showing various types of natural gas.

[By Bureau of Mines.]

	1	2	3	4	5	6	7
Methane (CH_4)	86.7	96.5	67.6	6.6	66.2	23.6	51.3
Ethane (C_2H_6)	9.5	.0	31.3	91.1	1.0	69.7	10.4
Carbon dioxide (CO_2)	1.7	1.4	.0	.0	30.4	2.5	.1
Nitrogen [a] (N_2)	2.1	2.1	1.1	2.3	2.4	1.3	38.2
Hydrogen sulphide (H_2S)	....	....	....	....	....	2.9	....
Oxygen (O_2)	.0	.0	.0	.0	.0	.0	.0
	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Heating value (British thermal units per cubic foot, at 0° C. and 760-millimeter pressure)	1,100	1,028	1,302	1,765	724	1,548	740
Specific gravity (calculated)	0.63	0.58	0.71	0.99	0.85	0.91	0.76

[a] Includes helium and the other inert gases.

1. Fullerton field, Orange County, Calif.
2. Caddo field, Caddo and Bossier parishes, La.
3. Oil City, Clarion County, Pa.
4. Titusville, Crawford County, Pa.
5. McKittrick field, Kings County, Calif.
6. Glasgow, Barren County, Ky.
7. Petrolia field, Clay County, Tex.

1, 4-6. Burrell, G. A., Seibert, F. M., and Oberfell, G. G., The condensation of gasoline from natural gas: Bur. Mines Bull. 88, pp. 21, 22, 1916.
2, 3, 7. Burrell, G. A., and Oberfell, G. G., Composition of the natural gas used in 25 cities: Bur. Mines Tech. Paper 109, p. 7, 1915.

After the paraffin hydrocarbons the chief constituents of natural gas are nitrogen and carbon dioxide. These substances occur in small proportion in most natural gas, but in some varieties they are important constituents. Oxygen is reported in many analyses, but its presence usually indicates contamination of the sample by air, and in such analyses the proportion of nitrogen reported is also unduly high. Hydrogen and carbon monoxide are reported, on the basis of indirect determinations, in many old analyses, but according to Burrell and Oberfell[57] these substances are really present in few if any natural hydrocarbon gases. Hydrogen sulphide is present in some gases in proportions as great as 2 or 3 per cent, though most gases do not contain even traces of it. Helium, argon, and the other inert gases are probably present in minor quantity in most natural gas, but they can be determined only by special methods, and in ordinary analyses they are reported with the nitrogen.

VARIETIES OF NATURAL GAS.

As natural gas is simply a mechanical mixture of the constituents mentioned above, it has no fixed composition and exhibits a wide range in chemical character. Several fairly well marked varieties may be distinguished, though between them all gradations exist. The helium-rich gases, however, belong to a distinct chemical type, and in order to understand the characteristics of this type a study of the accompanying analyses, which have been selected to illustrate the different varieties of natural gas, will be helpful.

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[55] See Burrell, G. A., Seibert, F. M., and Robertson, I. W., Analysis of natural gas and illuminating gas by fractional distillation at low temperatures and pressures: Bur. Mines Tech. Paper 104, 1915.

[56] Burrell, G. A., and Oberfell, G. G., Composition of the natural gas used in 25 cities: Bur. Mines Tech. Paper 109, p. 11, 1915.

[57] Op. cit., p. 11.

The table on page 36 indicates that several varieties of natural gas can be distinguished, as follows:

A. Pure hydrocarbon type (analyses 1 to 4). Most of the natural gas produced in the United States is of this type, containing 95 per cent or more of paraffin hydrocarbons and very minor proportions of carbon dioxide and nitrogen. Many subdivisions of the type may be made, however, according to the relative proportions of the hydrocarbons, conventionally expressed in terms of methane and ethane. Analysis 1, showing 9.5 per cent of ethane, represents the commonest variety and would not differ greatly from a composite analysis of all the natural gas produced in the United States. Analysis 2 represents a pure methane gas of the type produced chiefly in eastern Oklahoma and northwestern Louisiana. Analyses 3 and 4 presumably represent casing-head gases—gases occurring in the same sand with oil—and show high proportions of ethane and the heavier hydrocarbons. The gas represented by analysis 4 probably consists chiefly of ethane and propane, and carries butane, pentane, and hexane as well. All gas of the pure hydrocarbon type has a high heating value and is therefore the most valuable for industrial and domestic purposes.

B. Carbon dioxide type (analysis 5). Some of the gas produced in the California fields is notable for the high proportion of carbon dioxide it contains. Some California gases carry as much as 49 per cent of carbon dioxide, and a great many contain 10 or 15 per cent. Gas of the carbon dioxide type has naturally a rather low heating value, usually less than 900 British thermal units. Swamp gases of recent origin are also usually high in carbon dioxide, but true natural gas containing noteworthy proportions of this constituent occurs almost wholly in California.

C. Hydrogen sulphide type (analysis 6). Gas carrying as much as 2 to 3 per cent of hydrogen sulphide has been found in a number of localities, though most natural gas contains no hydrogen sulphide whatever. For this reason the hydrogen sulphide gases warrant recognition as a separate type, even though their characteristic constituent is invariably present only in small proportion.

D. Nitrogen type (analysis 7 and analyses on pp. 38–40). Natural gas carrying as much as 85 per cent of nitrogen occurs in Kansas, and gas carrying from 10 to 40 per cent has been found in Oklahoma, Texas, Ohio, and elsewhere. The nitrogen type of gas is of special interest here, for it is the only one in which noteworthy proportions of helium have been found. The heating value of the nitrogen type of gas is naturally low, and gas carrying 85 per cent of nitrogen is so nearly incombustible that it is commonly called wind gas.

It is evident that ordinary natural gas may be regarded simply as the lightest member of the petroleum series—gas, oil, and asphalt—and there is abundant evidence to indicate that natural gas, like oil and asphalt, is chiefly a product of the decay of organic matter that has been buried in the sediments. As there are idfferent kinds of organic matter, differing in composition, and as the conditions under which decay takes place are doubtless also variable, many different varieties of petroleum are known; and it must be recognized, furthermore, that petroleum may later undergo chemical and physical changes which lead to still further differentiation. Although the geochemistry of petroleum has not been extensively studied, it is the writer's opinion that the composition of most petroleum is determined chiefly by its geologic relations—that is, by the age and degree of deformation of the surrounding rocks and by the chemical character of those rocks and of the waters which they contain.[58] There is more evidence for this thesis as applied to oil than as applied to natural gas, for gas is relatively simple in composition and to a certain extent is the end product of the decomposition of oil; yet the composition of some gases is obviously controlled by their geologic relations. Much of the carbon dioxide in the California gas, for example, has probably been formed by oxidation of the hydrocarbons through contact with mineralized waters, and the hydrogen sulphide in some gases, at least, is formed by the reduction of sulphate waters by hydrocarbons.[59]

The nitrogen type of natural gas, is, however, difficult to account for.[60] The obvious supposition that the nitrogen represents the inactive residue of air that has been entrapped in the sediments is opposed by the fact that it contains a much smaller proportion of argon than does atmospheric nitrogen. The general occurrence of helium in high-nitrogen gases also suggests that the origin of the nitrogen is in some way related to that of the helium. (See pp. 38–40.) Moreover, the nitrogen can not well be explained as due to the peculiar composition of the organic matter from which the gas was derived, for the oil of Kansas, Oklahoma, and Ohio is low in nitrogen, whereas that of California, where no high-nitrogen gases are known, is exceptionally rich in the nitrogenous bases. This difference is brought out by the analyses of California, Ohio, and Kansas oils given in the following table:

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[58] Rogers, G. S., The Sunset-Midway oil field, Calif., Part II, Geochemical relations of the oil, gas, and water: U. S. Geol. Survey Prof. Paper 117, 1919.

[59] Idem, pp. 26–29.

[60] For a brief discussion of the origin of nitrogen in natural gas see Haworth, Erasmus, and McFarland, D. F., The Dexter, Kans., nitrogen gas well: Science, new ser., vol. 21, p. 191, 1904.

Ultimate analyses of petroleum.

	1	2	3	4	5	6
Carbon	84.17	86.51	84.57	85.46	85.43	85.63
Hydrogen	12.15	11.41	13.62	13.91	13.07	12.44
Sulphur	1.50	.74	.72	.48	.37	.37
Nitrogen	1.25	.58	.11	....	....	....
Undetermined	.93	.76	.98	.15	1.13	1.56
	100.00	100.00	100.00	100.00	100.00	100.00

1. Bardsdale, Calif. Mabery, C. F., and Hudson, E. J., On the composition of California petroleum: Am. Acad. Arts and Sci. Proc., vol. 36, p. 255, 1900.
2. McKittrick, Calif. Allen, I. C., and Jacobs, W. S., Physical and chemical properties of the petroleums of the San Joaquin Valley, Calif.: Bur. Mines Bull. 19, p. 28, 1911.
3. Findlay, Ohio. Mabery, C. F., On the composition of the Ohio and Canadian sulphur petroleums: Am. Chem. Jour., vol. 17, p. 727, 1895.
4. Welker, Ohio. Mabery, C. F., idem.
5. Cherryvale, Kans. Bartow, Edward, and McCollum, E. V., Kansas petroleum: Kansas Acad. Sci. Trans., vol. 19, p. 58, 1903.
6. Humboldt, Kans. Bartow, Edward, and McCollum, E. V., idem.

COMPOSITION OF HELIUM-BEARING GAS.

As stated in the foregoing sections, although at least traces of helium occur in most natural gas, noteworthy proportions have been found only in gas of the nitrogen type. The percentage of helium, moreover, seems to depend in a measure on the percentage of nitrogen, though there is no direct proportionality between the two, and the nitrogen-helium ratio varies greatly in different gases. On the other hand, there are some natural gases high in nitrogen which carry only small proportions of helium. The chemical characteristics of helium-bearing gas are shown by analyses 1 to 16, on page 39.

In the course of the present investigation the helium content of a large number of gases was determined (see pp. 96–109), but only a few complete analyses were made. Those given in the first table (p. 39) were therefore selected from the analyses, mostly of Kansas gas, published by Cady and McFarland.[61] In the second table are given a few ordinary analyses of gas from other localities, together with determinations of the helium content of gas from the same source. Samples for the ordinary analysis and for the helium determination of the Ohio gases, Nos. 23 and 24, were collected simultaneously, but the samples for the ordinary analyses of the other gases were collected several months or years before those for the helium determinations. As natural gas from the same well varies somewhat in composition from day to day, the exact ratio between helium and nitrogen in these samples can not be determined from the data given, though the ratios indicated are undoubtedly approximately correct.

More extensive data regarding the ratio of helium to nitrogen are given in figure 7 (p 40), which is based on all the analyses given by Cady and McFarland and on a few composite determinations similar to those in the accompanying table. As such determinations do not furnish data for computing the exact ratio they are plotted in the diagram as large open circles, whereas complete analyses on one sample are plotted as small dots.

The diagram brings out the wide variation in the ratio of helium to nitrogen in different gases but indicates that the average gas containing 10 per cent of nitrogen carries about 0.3 per cent of helium and that no gas containing 10 per cent of nitrogen is likely to carry more than 0.5 per cent of helium. Exceptions to this rule may be found, but the principle is believed to be sufficiently well founded to warrant the use of the nitrogen determination as a guide to the detection of helium-bearing gas; and in the writer's investigation of the distribution of helium a large number of ordinary analyses were collected and were used to supplement the data afforded by the direct tests for helium. Moreover, nitrogen is the chief factor in lowering the heating value of the Mid-Continent gases, and as general information concerning the heating value of a gas is usually not difficult to obtain, the rule that gases low in nitrogen are poor in helium is of great practical aid in locating the helium-rich varieties.

It should be noted, however, that gases low in heating value are not necessarily rich in helium. In the first place, low heating value may be due, as in California gas, to a high per-

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[61] Cady, H. P., and McFarland, D. F., The composition of natural gas, with special study of the constituents of Kansas gases: Kansas Univ. Geol. Survey, vol. 9, pp. 228–302, 1908.

Analyses of helium-bearing natural gas.

[By Cady and McFarland.]

	1	2	3	4	5	6	7	8
Methane (CH_4)	14.85	51.80	82.25	78.60	74.10	81.40	84.40	88.60
Ethane (C_2H_6)	.41	.00	.00	7.71	.00	.00	.00	.00
Olefines (C_2H_4, etc.)	....	.00	.12	.55	....	.00	.10	.00
Carbon dioxide (CO_2)	.00	.20	.61	.15	.54	.92	.00	.62
Oxygen (O_2)	.20	.10	Trace.	.30	.00	Trace.	Trace.	.31
Nitrogen (N_2)	82.70	46.40	16.40	12.13	24.85	17.22	15.10	10.20
Helium (He)	1.84	1.50	.616	.56	.51	.46	.40	.27
	100.00	100.00	99.996	100.00	100.00	100.00	100.00	100.00

	9	10	11	12	13	14	15	16
Methane (CH_4)	79.10	94.50	94.30	81.10	92.40	77.40	88.10	86.50
Ethane (C_2H_6)	7.44	.00	.75	11.95	.00	14.18	7.37	.00
Olefines (C_2H_4, etc.)	.77	.00	.00	.10	.10	.86	.65	.29
Carbon dioxide (CO_2)	.00	.00	1.94	.10	.81	.73	.24	1.35
Oxygen (O_2)	.00	.23	.24	.20	.15	.00	.00	.00
Nitrogen (N_2)	12.44	5.08	2.60	6.39	6.43	6.66	3.60	11.86
Helium (He)	.25	.183	.17	.159	.08	.167	.09	Trace.
	100.00	99.993	100.00	99.999	99.97	99.997	[a] 100.00	100.00

[a] Includes 0.25 per cent reported as hydrogen.

1. Dexter, Cowley County, Kans. Gas from 310-foot well supplying town. Collected in 1905.
2. Eureka, Greenwood County, Kans. Gas from wells drilled in northeast corner of town and furnishing town supply. Average depth of wells 375 feet. Collected October 25, 1906.
3. Fredonia, Wilson County, Kans. Pipe-line sample of gas used in Fredonia and furnished by wells 1,085 to 1,250 feet deep, 2 to 7 miles east, south, and northwest of town.
4. Elmdale, Chase County, Kans. Gas from wells about 150 feet deep. Collected October 6, 1906.
5. Moline, Elk County, Kans. Gas from wells about 1,150 feet deep south, east, and west of Moline. Collected June 24, 1906.
6. Lawrence, Douglas County, Kans. Sample of small flow of gas escaping from abandoned well about 1,200 feet deep. Collected July 4, 1906.
7. Olathe, Johnson County, Kans. Sample of gas supplied to town and derived from wells near Spring Hill, about 10 miles to the south. Average depth of wells 580 feet. Collected August 2, 1906.
8. Eudora, Douglas County, Kans. Gas from wells about 350 feet deep.
9. Augusta, Butler County, Kans. Gas from wells averaging 1,440 feet in depth. Sampled August 4, 1906.
10. Iola, Allen County, Kans. Sample of gas supplied to town of Iola and derived from wells near by. Sampled June 10, 1906.
11. Pipe-line sample of gas supplied to town of Lawrence, Kans., and derived chiefly from fields in Allen and Neosho counties. Collected December 12, 1906.
12. Arkansas City, Cowley County, Kans. Gas from well 750 feet deep.
13. Caney, Montgomery County, Kans. Gas from well 1,550 feet deep, 2 miles east of Caney. Collected July 14, 1906.
14. Marion, Grant County, Ind. Sample received August 25, 1906.
15. Morgantown, Monongalia County, W. Va. Sample from well about 1,800 feet deep, 10 miles west of Morgantown. Producing sand probably Big Injun. Sampled August 18, 1906.
16. Pierre, Hughes County, S. Dak. Gas from shallow wells.

Analyses of helium-bearing natural gas.

[Eudiometric analyses by various chemists; helium later determined on different samples from same source by C. W. Seibel.]

	17	18	19	20	21	22	23	24
Methane (CH_4)	10.54	38.94	50.6	49.08	30.33	57.89	77.3	86.1
Ethane (C_2H_6)	1.64	4.80	10.9	3.89	26.69	16.89	7.6	4.6
Higher hydrocarbons (C_3H_8, etc.)	.00	.00	....	.00	.00	.00	....	....
Carbon dioxide (CO_2)	.13	.24	.1	.40	.49	.24	.0	.0
Oxygen (O_2)	.00	.32	.0	.00	.00	.00	.0	.0
Residue (nitrogen, helium, etc.)	87.69	55.70	38.4	46.67	42.51	24.97	15.1	9.6
	100.00	100.00	100.00	100.00	100.02	99.99	100.00	100.3
Helium (He)	2.13	1.94	.945	.94	.39	.27	.43	.40

17. Augusta field, Butler County, Kans. "Wind gas" occurring at depth of 400 to 600 feet. Analysis by H. C. Allen, University of Kansas.
18. Sedan district, Chautauqua County, Kans. Gas from Fleming & Wadsworth well, sec. 27, T. 33 S., R. 11 E. Depth 375 feet. Analysis by H. C. Allen.
19. Petrolia field, Clay County, Tex. Pipe-line gas. Analysis by Bureau of Mines on sample collected in October, 1914; helium determined on sample collected in November, 1917.
20. Sedan district, Rogers pool, Chautauqua County, Kans. Gas from T. E. Barr well 1, sec. 36, T. 33 S., R. 10 E. Depth about 690 feet. Analysis by H. C. Allen.
21. Billings field, Noble County, Okla. Gas from E. N. Gillespie gas well, sec. 21, T. 23 N., R. 2 W. Depth of sand 1,036 feet. Analysis by Empire Gas & Fuel Co.
22. Morrison field, Pawnee County, Okla. Gas from Miller well 1. Analysis by Empire Gas & Fuel Co.
23. Vinton County field, Ohio. Gas from Ohio Fuel Supply Co.'s well 1991, sec. 1, T. 9 N., R. 18 W. Gas from Clinton sand at 2,498 feet. Analysis by Bureau of Mines.
24. Vinton County field, Ohio. Gas from Ohio Fuel Supply Co.'s well 634, sec. 1, T. 8 N., R. 18 W. Gas from Berea sand at 660 feet. Analysis by Bureau of Mines.

centage of carbon dioxide. Secondly, even if it is due to nitrogen a high percentage of nitrogen does not necessarily indicate a gas rich in helium. Some of the northern Oklahoma gases carry from 20 to 40 per cent of nitrogen and only 0.2 to 0.4 per cent of helium. The range in the ratio of nitrogen to helium in a few typical gases is shown in the following table:

Ratios of nitrogen to helium in natural gas.

Field.	Nitrogen (N_2) (per cent).	Helium (He) (per cent).	Ratio N_2He.
Morrison, Okla	25.0	0.22	114
Ponca City, Okla	40.1	.36	111
Billings, Okla	42.5	.39	109
Loco, Okla	16.2	.17	95
Otto, Kans	57.8	1.04	55
Dexter, Kans	82.7	1.84	45
Augusta, Kans	88.0	2.00	44
Vinton County, Ohio	15.1	.43	35
Sedan, Kans	55.7	1.94	29
Fredonia, Kans	16.4	.62	26
Vinton County, Ohio	9.6	.40	24
Elmdale, Kans	12.1	.56	22
New Albany, Kans	9.8	.49	20

It is conspicuous that the highest ratios are found in northern Oklahoma, in gases such as those of the Ponca City, Billings, Morrison, Pearson, and Myers fields, all of which lie near the southern extremity of the rich helium-bearing area. On the other hand, some of the lower ratios are in the gases of central Kansas fields, which lie near the north end of the area. It seems, however, that the gases in which the ratio is unusually low are rather poor in both helium and nitrogen.

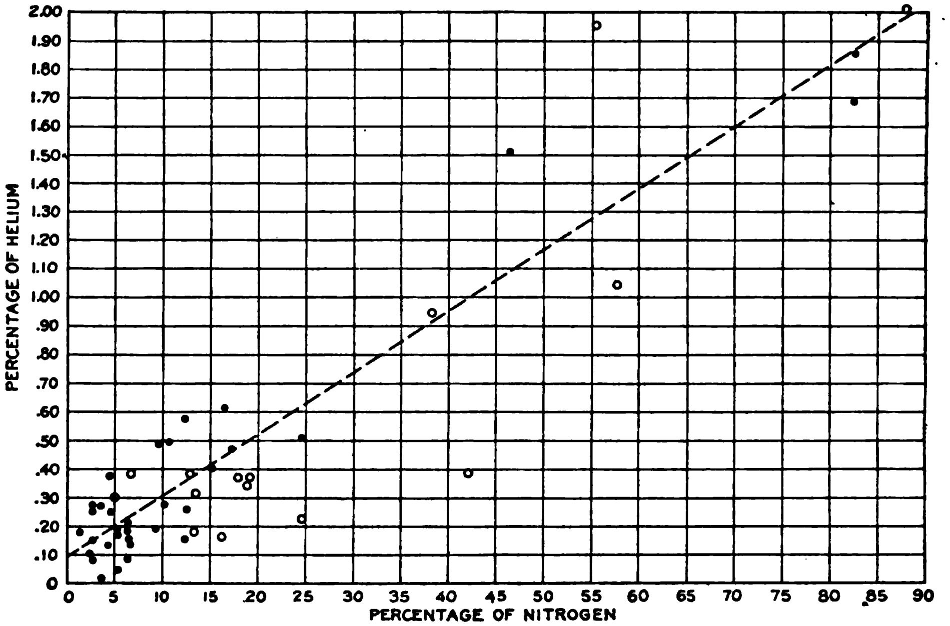

FIGURE 7.—Diagram showing relation of helium to nitrogen in 50 samples of natural gas. Points based on complete analyses of one sample indicated by dots; points based on determinations of helium in one sample and of nitrogen in another indicated by open circles.

DETERMINATION OF HELIUM IN NATURAL GAS.

DEVELOPMENT OF METHODS.

Identification of the presence of helium in most gaseous mixtures is accomplished without great difficulty by means of the spectroscope, provided the proportion of helium present is not too small. The precise quantitative determination of the helium, however, requires its separation from the other gases composing the mixture, and this is a more difficult matter. Carbon dioxide, oxygen, and the hydrocarbons are easily eliminated, but special methods are necessary for the removal of nitrogen and the inert gases.

Ramsay in his early researches on helium removed the nitrogen by sparking, which is a slow and tedious process. Sparking under various conditions was at first used by other investigators, but Dewar's discovery that nitrogen is absorbed by charcoal cooled with liquid air, whereas helium is not, has served to facilitate greatly the separation of the two elements. Dewar's principle is now generally used by most English and American investigators, although some French scientists prefer the more laborious chemical methods of removing nitrogen.

Cady and McFarland in their original research on helium in natural gas adopted Dewar's principle to remove nitrogen and all the other common constituents of the gas and constructed an apparatus in which the whole operation could be efficiently conducted. Essentially the same method, with a similar apparatus, was used by Prof. Cady at the outset of the Government's investigation and also by C. W. Seibel in his continuation of the work. The method is one of unusual interest because of the short time required for accurate determinations, and Mr. Seibel, who analyzed most of the samples discussed in this report, has courteously furnished the following description of it:

APPARATUS AND METHOD OF PROCEDURE.

By C. W. Seibel.

The apparatus used in the quantitative determination of helium from either natural gas or concentrates was essentially the same as that employed by Cady and McFarland in their earlier work.[63] It is not so well known, however, as to preclude description here. The method of analysis also was similar to that of the original work, but modifications have been added from time to time, by Dr. Cady and his coworkers, and these have been included in the following account.

The apparatus, which is shown in Plate IV, is composed of the following parts: F is an automatic single-fall Sprengel vacuum pump, of the ordinary 4-tube type. The tubes are about 83 centimeters long and 6 millimeters in outer diameter except the capillary fall tube, which is a heavy capillary tube 1½ millimeters in inner diameter and 110 centimeters long and the free end of which is bent upward so as to deliver into the collecting bulb j. This bulb is of 50 cubic centimeters capacity and has a capillary stopcock on the top. The bulb g is an air trap, the top of which is sealed after the pump is filled with mercury. The four pump tubes are joined together at the bottom with heavy-walled stethoscope tubing. Screw clamps here serve very well to regulate the speed of the pump. The mercury is pumped from the main reservoir m to the pump supply reservoir h through k and k_1 by means of an auxiliary Nelson vacuum pump u, attached to the supply reservoir at i. A few iron wires inserted into the end of the suction pipe at k cause alternate slugs of mercury and air to be drawn up k and k_1 and into h. By means of a cork float to which k is fastened, any level of mercury desired can be maintained in the supply reservoir. l is the mercury overflow outlet of the supply reservoir, the excess mercury flowing down the tube which dips below the mercury in trap l_1. This trap prevents the loss of the vacuum in h. d and e are mercury and water vapor traps and, being of small tubing, are so arranged that they go into one Dewar tube, which affords considerable saving in liquid air and space. During the analysis these tubes are immersed in liquid air and serve to prevent water vapor or mercury vapor from entering the spectrum tube. The spectrum tube c is so constructed that the light for the spectroscope may be taken either from the end of the capillary or along it. It is excited by a 6-volt spark coil giving a spark of about 1 centimeter in air. The gas, having stood over charcoal at the temperature of liquid air and passing through this tube excited by the spark coil, emits a glow which when viewed through the spectroscope tells at a glance whether or not the gas is pure or contaminated with nitrogen. Any appreciable amount of nitrogen can be told by the color of the tube alone, for nitrogen will cause the spectral tube to give a purplish glow, while pure helium unless at very low pressure is yellow. The bulbs b_1, b_2, and b_3 are made of glass carefully annealed. They contain about 20 grams of coconut charcoal each, with plugs of glass wool at either end, and are of such dimensions that they will easily fit in 40 by 200 millimeter Dewar tubes. They are connected with one another by being sealed in such a manner as to make one continuous train. Three-way glass stopcocks are inserted in the train in such wise that tubes b_1 and b_2 may be used in series, and b_3 may be in series with the other two or by-passed at will. These stopcocks are also arranged in such a manner that the three charcoal tubes can be conveniently exhausted by the auxiliary pump. a_2 is a glass liquefaction bulb of 40-cubic centimeter capacity with a mercury manometer, a_3, attached. By means of this manometer the pressure in a_2 can be determined at any time. The liquefaction bulb is so constructed that the gas must go nearly to the bottom of the tube before it can get into the connecting tube between a_2 and b_1. The curlicues inserted into different parts of the apparatus serve as expansion joints. The two tubulated bottles p and q are used for measuring gas samples and are of 2-liter capacity. They are so arranged that p can be filled with water which has been saturated with helium, and then the water displaced by natural gas, the water going into q and vice versa. After the bottles are leveled up a pinch clamp on the connecting tube between the two serves to maintain atmospheric pressure in p, and a pinch clamp on the inlet tube to prevent the escape of gas while weighing, etc. o is a solution balance for weighing p and should have a sensibility of 1 gram. v is a cylinder for collecting samples from the field. n is an electric heater for heating the charcoal bulbs while they are being exhausted. u is a Nelson two-stage vacuum pump for exhausting the charcoal bulbs while being heated, and for use as an auxiliary vacuum pump to lift the mercury into the supply reservoir h. The switches r, s, and t control the spark coil for the spectrum tube, motor for vacuum pump, and heater, respectively.

The apparatus is first evacuated—the charcoal bulbs by the Nelson pump and the spectrum tube and traps by the mercury pump to a black vacuum. The charcoal bulbs are heated to 200° C. and the evacuation is continued for about 20 minutes. After being allowed to cool, the charcoal bulbs, liquefaction bulb, and water and mercury vapor trap are immersed in liquid air, which is contained in silvered Dewar tubes. While the charcoal bulbs are cooling, the gas, which is held in the sampling cylinder under a pressure of several pounds, is forced into the tubulated measuring flask. A pinch clamp is put on the end of the inlet tube, the bottles are leveled, a pinch clamp is placed on the connecting tube, and the flask p is weighed on the solution balance. A portion of this gas, approximately 1 liter, is then allowed to flow from the bottle through the rubber tube to the evacuated space of the liquefaction bulb, the flow being controlled by stopcock a_1, and the rate of inlet being determined by the action of the manometer. At the temperature of liquid air the hydrocarbons are liquefied, and the pressure on the manometer adjoining indicates whether or not the gas is of high nitrogen content. If the nitrogen content is high the manometer will indicate considerable pressure within the tube, which can be due only to unliquefied nitrogen or helium, though of course a small amount of it is always due to the partial pressure of methane and other hydrocarbons. The unliquefied portion, consisting of nitrogen, helium, and some of the hydrocarbons, is admitted, in small amounts, to the first charcoal bulb, which of course is under a very high vacuum, and then to the second. This procedure is repeated until the manometer will rise no farther, indicating that all the helium and nitrogen and some methane have gone into the charcoal bulb and that the pressure in the liquefaction bulb is due only to methane and the higher hydrocarbons. The gas is allowed to stand in the charcoal bulbs for about three minutes, and then communication is made between the charcoal bulb, the spectrum tube, and the pump. The gas not adsorbed by the charcoal is pumped off and delivered into the collecting tube j. As coconut charcoal at the temperature of liquid air will absorb relatively large volumes of all gases except helium, neon, and hydrogen, and as neon and hydrogen do not occur in troublesome quantities, the gas delivered by the pump should be pure helium. However, to avoid danger of the charcoal bulbs becoming supersaturated with nitrogen or the possibility of an air leak developing, so that nitrogen would be pumped off with the helium, constant watch is kept of the spectrum tube by means of a spectroscope, small amounts of nitrogen being very easily detected in this way. If nitrogen appears early enough, the pump is stopped, the third charcoal bulb, b_3, is put into communication with the pump, and the nitrogen diffuses back into it, and then by pumping the helium, which is in b_1 and b_2, through b_3, a satisfactory determination can often be obtained without having to repeat the entire experiment.

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[63] Am. Chem. Soc. Jour., vol. 29, p. 1522, 1907.

If the spectroscope indicates nothing but helium, the pumping is continued until the spectrum tube shows cathode rays or goes out. The gas which has been collected in j at the bottom of the mercury pump is transferred to a small Hempel burette, and its volume is determined. After the tubulated flasks are releveled, the one containing gas is again weighed. The difference in weight, in grams, of the flask as first weighed full of gas and after part of the gas has been used and has been displaced with water gives the volume of gas used in cubic centimeters. If care is taken to see that the bottles are carefully leveled and stand always in the same relative position while being weighed, the necessary accuracy in measuring the volume of the natural-gas sample used may be easily obtained. All volumes are reduced to standard condition and the percentage of helium is calculated.

This method, though somewhat long, taking on an average of about 1½ hours for a determination, in the hands of one who is familiar with it gives surprisingly good results, repeated checks within 0.02 per cent being easily obtained.

For a satisfactory apparatus a good deal depends on the stopcocks used and the lubricant employed. A stopcock should be of the best quality obtainable, and the best lubricant has been found to be that as given in Ramsay and Travers's book "Experimental study of gases," namely, two parts of pure rubber clippings to one part of vaseline and one-eighth part of hard paraffin wax heated until a homogeneous mixture is obtained. A good stopcock, when properly lubricated, will appear perfectly clear, showing no rings or air bells whatever.

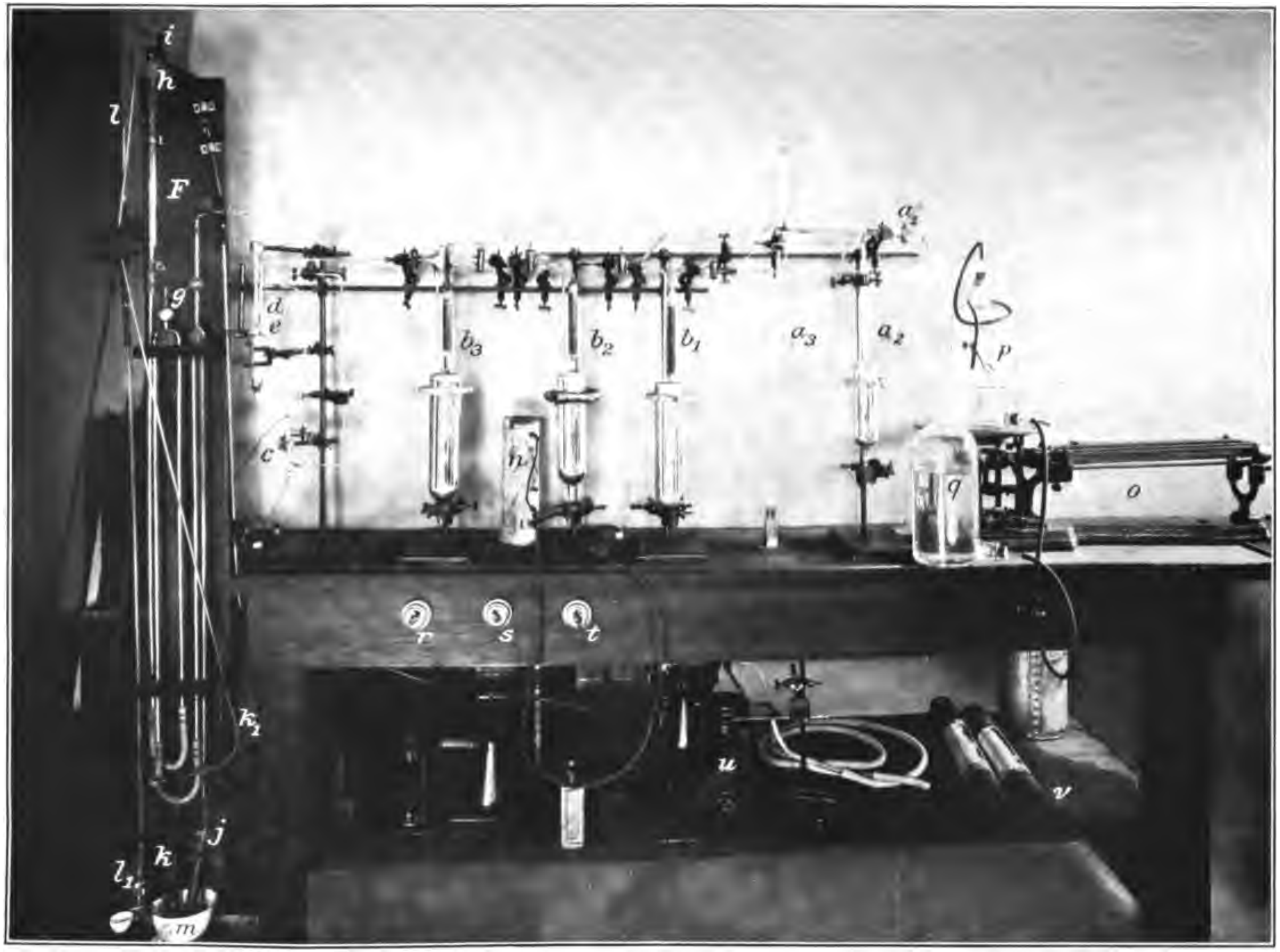
The writer wishes to take this opportunity to express his appreciation for the help and advice afforded him by Dr. H. P. Cady, under whose personal direction the early part of the work was performed, and by Dr. R. B. Moore, at Fort Worth, during the later part of the work; also for the assistance of Messrs. H. M. Eastman and J. B. Ramsay, who analyzed some of the samples toward the end of the field work, and to Miss Emily V. Burger, of the University of Kansas, who analyzed 13 samples while the writer was on a trip to the Fort Worth plants.

OCCURRENCE OF HELIUM IN MINERALS AND IN OTHER GASES.

GENERAL DISTRIBUTION OF HELIUM.

Although helium was discovered on the earth only 25 years ago and for some time thereafter was regarded as one of the rare elements, it is now known to be widely distributed through the earth's crust. As already described, helium was discovered on the earth in the gas given off by uraninite, and the researches of Strutt and others have shown that a great variety of other minerals and rocks contain helium in small proportions. Only a few months after its discovery helium was found to be a constituent of the atmosphere and of the gas given off by a mineral spring, and it has since been found to occur in the gases emitted by a great many other springs. Helium has been found also in mine gases and in volcanic gases, as well as in natural gas.

The discovery in 1903 of the fact that helium is a product of the decay of the radio-elements, which were known to be widely disseminated, furnished to most observers an adequate explanation of the occurrence of helium in so many natural substances. There is no doubt that the minute proportions of helium found in most minerals may be accounted for in this way, but the great volumes found in natural gas are more difficult to explain. Before discussing the origin of helium in natural gas it



APPARATUS USED IN QUANTITATIVE DETERMINATION OF HELIUM.

will therefore be desirable to review the occurrences of helium in minerals and in other gases.

HELIUM IN MINERALS AND ROCKS.

HELIUM CONTENT OF MINERALS.

The discovery of helium in uraninite naturally led to a search for it in other minerals, with the result that only a year or so after the element itself was discovered a number of minerals were found to be helium bearing. When the relations of helium to the radio-elements became known, a great many more minerals were tested, the amounts of helium and of radium and thorium in each being determined quantitatively, so that extensive data on the distribution of helium in minerals are now available. A very great majority of all the minerals tested have proved to contain at least traces of helium, the proportion varying in general with the proportions of the radio-elements. Some minerals that contain no radioactive substances, however, have been found to contain helium in considerable quantities.

The first observations on the occurrence of helium in minerals were made by Ramsay and Travers[63] in 1897. They found that the rare-earth minerals fergusonite, monazite, samarskite, columbite, pitchblende, and malacone contain helium "up to 1.5 cubic centimeters per gram." The malacone contains argon as well.[64] Specimens of cinnabar, cryolite, apatite, barite, scapolite, and cobalt ore gave no helium or argon. Five meteorites were tested with negative results, but the meteorite from Augusta County, Va., proved to contain helium.

Chamberlin,[65] in connection with his studies of the gases in rocks, determined the composition of the gases given off by heating pitchblende and carnotite in a vacuum as follows:

Composition of the gases extracted from pitchblende and carnotite.

[Volumes per unit volume of rock.]

	Pitchblende, Beaver County, Colo.	Carnotite, Colorado.
Carbon dioxide	....	2.46
Carbon monoxide	0.24	.23
Methane	.03	.02
Hydrogen	.07	.05
Nitrogen	.27	.22
Helium	.37	.04
	.98	3.02

By far the most extensive and systematic investigation has been made by R. J. Strutt, who determined the helium and the radium and thorium content of a great variety of rare and common minerals. In his earlier experiments Strutt extracted the helium by heating a considerable quantity of the powdered mineral to redness and purifying the gas thus obtained first by sparking and finally by absorption in cooled charcoal. The extraction of helium by the use of red heat is by no means complete, the helium extracted being probably only about half that which the mineral contains. The table on page 44 shows the helium content of some of the minerals examined by Strutt[66] and also the value of uranium oxide as calculated from the radium content.

In discussing his results Strutt pointed out that as helium is generated by the decay of uranium, the ratio of helium to uranium should be of the same order in all minerals, though greater in ancient minerals than in recent ones. In order to test this hypothesis, Strutt next examined groups of similar minerals from different geologic horizons. In this investigation the crude method of extracting the helium by heat was abandoned, and a method of fusion and solution, which permitted complete extraction of helium, was used. Thorium

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[63] Ramsay, William, and Travers, M. W., The gaseous constituents of certain mineral substances and waters: Roy. Soc. London Proc., vol. 60, p. 442, 1897.

[64] Kitchin, E. S., and Winterson, W. G., Malacone, a silicate of zirconium containing argon and helium: Chem. Soc. Jour., vol. 89, p. 1568, 1906.

[65] Chamberlin, R. T., The gases in rocks: Carnegie Inst. Washington Pub. 106, p. 20, 1908.

[66] Strutt, R. J., Helium and radioactivity in rare and common minerals: Roy. Soc. London Proc., ser. A, vol. 80, p. 572, 1908; The accumulation of helium in geologic time: Idem, vol. 81, p. 272, 1908; vol. 83, p. 96, 1909; vol. 84, p. 194, 1910.

Helium content of certain minerals.

[Helium extracted by heat, except as otherwise noted.]

Mineral.	Locality.	Helium (cubic millimeters per gram).	U_3O_8 (grams per 100 grams).
Rare-earth minerals:			
Pitchblende [a]	Joachimsthal, Austria	107	73.5
Samarskite [a]	North Carolina	1,500	10.3
Cyrtolite [a]	Llano County, Tex.	1,150	3.67
Sipilite [a]	Little Friar Mountain, Va.	590	2.86
Euxenite [a]	Arendal, Norway	730	2.84
Eudialite	Greenland	1.46	3.9×10^{-3}
Gadolinite	Hitteroe, Norway	10.5	4.2×10^{-2}
Keilhauite	Alve, Norway	16.3	1.4×10^{-1}
Niobite	Haddam, Conn.	3.60	3.0×10^{-2}
Apatite	Canada	1.16	4.5×10^{-3}
Cerite	Bastnaes, Sweden	1.26	9.3×10^{-3}
Fluorite	Ivigtut, Greenland	27.00	4.9×10^{-4}
Ore minerals and native elements:			
Galena	Nenthead, Cumberland, England	.0007	9.0×10^{-6}
Cinnabar	Almaden, Spain	.0	
Bornite	Cornwall, England	.12	3.2×10^{-3}
Stibnite	New South Wales	.007	1.3×10^{-4}
Sphalerite	Wrexham, Denbigh, Wales	.0007	7.0×10^{-5}
Tin pyrites	Cornwall, England	.0046	3.1×10^{-5}
Iron (meteoric)	Meteorite of Augusta County, Va.	$<.0016$	7.8×10^{-6}
Graphite	Borrodaile, Cumberland, England	.04	1.1×10^{-3}
Hematite	Cumberland, England	.07	1.57×10^{-3}
Hematite [b]	Frizington, Cumberland, England	.16	1.28×10^{-3}
Hematite [b]	County Antrim, Ireland	.012	2.64×10^{-4}
Limonite [b]	Forest of Dean, Gloucestershire, England	.15	10.3×10^{-4}
Cassiterite	St. Austell, Cornwall, England	.04	3.9×10^{-6}
Wolframite	Illogan, Cornwall, England	1.16	1.05×10^{-3}
Vanadinite	Dumfries, Scotland	.0	
Miscellaneous:			
Barite	St. Bees, Cumberland, England	.0008	4.4×10^{-4}
Celestite	Zate, Gloucestershire, England	.0004	2.6×10^{-4}
Calcite	Cumberland, England	$<.0006$	2.2×10^{-6}
Quartz	Ilfracombe, Devonshire, England	.0012	2.31×10^{-6}
Flint (from chalk)	Brandon, Norfolk, England	.0002	1.33×10^{-4}
Garnierite	Oregon	.0027	
Beryl [c]	Acworth, N. H.	12.8	1.4×10^{-4}
Beryl	Chester, Pa.	6.69	2.2×10^{-3}
Phosphatized shark teeth [b]	Florida	.0017	2.48×10^{-2}
Phosphatic nodules [b]	Potton, Bedfordshire, England	.021	5.83×10^{-3}
Phosphatic limestone [b]	Chirbury, Shropshire, England	.056	7.90×10^{-4}

[a] Method of extracting helium not stated.
[b] Helium extracted by dissolving mineral.
[c] Helium extracted by fusion and solution.

was also determined, so as to permit calculation of the ratio between helium and both the elements that generate it. In the table on page 45 the figures under the heading "Total equivalent U_3O_8" are obtained by adding the quantity of U_3O_8 and 0.203 times the quantity of ThO_2, the assumption being that 1 gram of ThO_2 is equivalent to 0.203 gram of U_3O_8, so far as helium generation is concerned, and the helium ratio is obtained by dividing the helium in cubic centimeters per gram by the total equivalent uranium oxide.

Reserving for discussion below the significance of the helium ratio as an indication of the age of minerals, we may note here that a great variety of minerals contain helium and that in general its presence appears to be explained by the presence of uranium or thorium. The proportion of helium is therefore not characteristic of any mineral species but is generally very different in different specimens.[67] In pitchblende, however, the quantity of helium is generally very low in proportion to that of uranium, the ratio in the Joachimsthal variety being only 0.146, and on the other hand there are certain minerals in which the quantity of helium is far greater than can be explained by the uranium or thorium present. The beryls, for example, are generally very rich in helium and very poor in the radio-elements, the ratio in the Acworth beryl being 9,140. Piutti examined 26 beryls and other glucinum-bearing minerals that contained no uranium or thorium and found helium in varying quantities in all of them.[68]

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[67] Piutti, A., Sur les minéraux nonradioactifs contenant de l'hélium: Le Radium, vol. 7, pp. 146, 178, 1910. Debierne, A., Expériences diverses sur la production de l'hélium: Annales phys., vol. 2, p. 478, 1914.

In this connection it may be noted that Valentiner[71] examined blue rock salt and reported 0.13 cubic centimeter of helium per 100 grams, as compared with Strutt's figure of 0.0233 cubic centimeter per 100 grams in the ordinary variety.

Helium, uranium, and thorium content of zircon, sphene, and thorianite.[a]

Mineral.	Geologic age.	Locality.	Content per gram of mineral.				Helium ratio.
			Helium (cubic centimeter ×10⁻⁴).	U_3O_8 (grams × 10⁻⁴).	ThO_2 (grams × 10⁻⁴).	Total equivalent U_3O_8 (grams × 10⁻⁴).	
Zircon	Tertiary	Vesuvius	<0.4	38.0			<0.01
Do	do	Expailly, Auvergne, France.	2.12	3.72	0.0	3.72	.57
Do	Paleozoic	Green River, N. C	225.0	12.9	30.1	19.0	13.4
Do	do	Kimberley, South Africa.	323.0	10.8	1.32	11.1	29.2
Do	Ancient	Ceylon	283.0	10.1	4.0	10.9	26.0
Do	Archean	Sebastopol, Ontario	114.0	1.83	.92	2.02	56.6
Sphene	do	Cold Spring, N. Y	101.0	1.87	4.23	2.73	37.0
Do	do	Renfrew County, Ontario.	94.8	4.30	1.98	4.70	20.2
Do	do	do	176.0	1.72	4.82	2.70	65.0
Do	do	Twederstrand, Norway.	33.6	.772	4.73	1.73	19.4
Do	do	do	45.4	.921	.920	1.11	40.8
Do	do	Arendal, Norway	123.0	2.46	4.34	3.34	36.8
Thorianite	do	Ceylon	93,000.0	2,450.0	6,544.0	3,780.0	24.6
Do	do	do	78,000.0	1,310.0	7,265.0	2,785.0	27.9

[a] Strutt, R. J., The accumulation of helium in geological time: Roy. Soc. London Proc., ser. A, vol. 83, p. 298, 1909; vol. 84, p. 194, 1910.

Another group of helium-bearing minerals that are poor in radioactive substances are the potash salts. Potassium is indeed radioactive itself, but so far as known it emits no alpha rays and therefore does not generate helium.[69] Strutt[70] examined a number of the Stassfurt potash minerals and found abnormally large quantities of helium in some and very small quantities in others. His quantitative results are given in the following table:

Helium content of some Stassfurt salts.

	Helium (cubic millimeters per 100 grams).	U_3O_8 (grams per 100 grams).	Helium (cubic centimeters per gram U_3O_8).
Halite ($NaCl$)	0.0233	7.1×10^{-6}	3.3
Sylvite (KCl)	.55	2.15×10^{-6}	256.0
Carnallite ($KMgCl_3.6H_2O$).	.151	3.23×10^{-6}	47.0
Kieserite ($MgSO_4.H_2O$)	.0179	6.47×10^{-5}	.277

HELIUM CONTENT OF ROCKS.

Comparatively few determinations of the helium content of rocks have been made, and most of the minerals examined for helium are not important as rock-forming varieties. Ramsay and Travers,[72] in their early research on the distribution of helium, examined gneiss, lava from Iceland, serpentine, and blue clay from Kimberley, South Africa, with negative results. Gautier, in his classic investigation of the composition of gases in rocks,[73] reports that helium was never found except in spectroscopic traces, though the gases of many rocks are rich in nitrogen and in argon. Strutt, however, examined four igneous rocks and found the proportions of helium, argon, and uranium oxide shown in the table on page 46.[74]

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[68] Piutti, A., L'elio nei minerali di glucinio: R. Accad. Lincei Atti, vol. 22, pt. 1, pp. 140, 671, 1913.

[69] Campbell, Norman, The beta rays from potassium: Cambridge Philos. Soc. Proc., vol. 14, pt. 2, p. 211, 1907.

[70] Strutt, R. J., On helium in saline minerals, and its probable connection with potassium: Roy. Soc. London Proc., ser. A, vol. 81, p. 278, 1908.

[71] Valentiner, Siegfried, Heliumgehalt im blauen Steinsalz: Kali, vol. 6, pp. 1-3, 1912.

[72] Ramsay, William, and Travers, M. W., The gaseous constituents of certain mineral substances and waters: Proc. Roy. Soc. London, vols 60, p. 442, 1897.

[73] Gautier, A., Produits gazeux dégagés par la chaleur de quelques roches ignées: Compt. Rend., vol. 132, p. 58, 1901; Sur l'existence d'azotures, argonures, arséniures et iodures dans les roches cristalliniennes Idem, p. 932.

[74] Strutt, R. J., Helium and radioactivity in rare and common minerals: Roy. Soc. London Proc., ser. A, vol. 80, p. 586, 1908.

Helium, argon, and uranium oxide in igneous rocks.

Rock.	Locality.	Helium (cubic millimeters per gram).	Argon (cubic millimeters per gram).	U_3O_8 (grams per 100 grams).
Granite	Cornwall, England	0.029	0.010	8.7×10^{-4}
Diorite	Mount Sorrel, Leicestershire, England	.005	.016	2.0×10^{-4}
Phonolite	Trafrain Law, Haddingtonshire, England	.0086	.013	....
Basalt	Ireland	.0019	.0025	1.9×10^{-4}

Strutt used red heat in extracting the helium from these rocks, and it may therefore be presumed that the proportions shown in the table are only about half the true values. Strutt reports that limestone and gypsum generally contain very little if any helium.

TIME CALCULATIONS BASED ON HELIUM CONTENT.

As the radio-elements in minerals are continually breaking down and emitting helium at a constant rate, it is obvious that the ratio of helium to uranium and thorium should be greater in ancient minerals than in recent ones, and all of Strutt's later work on helium in minerals was designed to investigate this relation between helium ratio and age. His work on limestones, phosphatic rocks, and iron ores of diverse ages yielded results of negative value in this connection, for the increase of the helium ratio with age proved to be highly irregular. Practically all the sphenes he examined were of Archean age and showed divergent ratios, but a series of zircons yielded more concordant results, the helium ratio increasing from 0.01 in a Tertiary variety to 56.6 in an Archean variety. (See p. 45.) Strutt then attempted to determine experimentally the rate at which helium is produced and, having obtained a figure in close agreement with that obtained by calculation,[75] declared the helium ratio to be a reliable index of the antiquity of minerals and therefore a measure of the length of geologic time. (See table, p. 45.) On this basis Strutt concluded that the Archean sphene of Renfrew County, Ontario, is 710,000,000 years old.

It will be observed that this far-reaching conclusion involves three assumptions—(*a*) that the rate of decay of the radio-elements is invariable; (*b*) that all the helium generated in the mineral has been retained by it during geologic time; and (*c*) that the mineral contained no helium at the outset and has since absorbed none from extraneous sources. A corollary of the general theory which makes it of interest in connection with the origin of helium in natural gas is the tacit assumption that all helium is of radioactive origin.

(*a*) The rates of decay of the radio-elements have been measured by a number of observers, and although the adopted figures are still subject to modification as more data become available, there seems little likelihood of extensive change. The law of decay is unaffected by such variations in temperature and pressure as can be produced in the laboratory, though its constancy under the temperatures and pressures existing in the earth is debatable. (See p. 12.) Moreover, it is obvious that the law of decay has been measured only for a period of a few years, whereas its application to the age of minerals involves extrapolating it to millions or billions of years.

(*b*) Strutt[76] has shown that there is a rapid leakage of helium from minerals and that weathered or water-worn minerals probably contain only a part of the helium that has been generated in them. The mere fact that enormous volumes of helium are found in natural hydrocarbon gas and in other gases of course also indicates that helium is migratory. The escape of helium, then, may result in greatly decreasing the helium ratio and thus the apparent age of a mineral.

(*c*) As helium is a widely distributed element and is found in volcanic and hot-spring gases, it is not unreasonable to suppose that helium is occluded or dissolved in igneous magmas and that when crystallization begins some of the helium enters into the forming minerals just as nitrogen, argon, hydrogen, and other gases do.[77] The quantity so occluded might be very small in proportion to that later generated in the mineral by radioactivity, but it also appears possible for helium to enter the mineral after its formation and thus still further to increase its apparent age. Jaquerod and Perrot [78] have shown that quartz absorbs helium at a measurable rate even at so low a temperature as 220° C., and Piutti [79] found that certain other fused salts and minerals also absorb it at moderate temperatures. The very common presence of helium in beryls, in quantities far larger than can be accounted for by the radio-elements present, is probably to be explained in this way, and it is very possible that the helium in potassium minerals has also entered from some extraneous source.

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[75] Strutt, R. J., Measurements of the rate at which helium is produced in thorianite and pitchblende, with a minimum estimate of their antiquity: Roy. Soc. London Proc., ser. A, vol. 84, p. 379, 1910.

[76] Strutt, R. J., The leakage of helium from radioactive minerals: Roy. Soc. London Proc., ser. A, vol. 82, p. 166, 1909.

[77] See the papers by Gautier and Chamberlain cited on pp. 43, 45, 51.

If minerals under some conditions give up helium and under others absorb it, the writer believes that little reliance can be placed on the helium ratio as a basis for age calculations. The widely divergent ratios obtained by Strutt for minerals of the same geologic age and even from the same locality certainly indicate that disturbing factors have affected the ratio, and there is every reason to believe that these factors may have been additive, increasing the apparent age, as well as subtractive. Attempts have also been made to compute age by the ratio of uranium to lead in minerals, but they need not be discussed here.[80]

Although the attempt to calculate the age of minerals in years from the helium ratio appears to be scarcely warranted, it is nevertheless recognized that the general evidence afforded by the distribution of helium in minerals suggests, with several outstanding exceptions, that the helium is a product of radioactivity.

HELIUM IN MINE GASES.

Apparently helium has been sought for in only a few mine gases, but it has been identified in the fire damp of several coal mines in northern France and Belgium, and in the gas escaping in a potash mine near Stassfurt, Germany. As the gas escaping in many mines is known to be high in nitrogen,[81] however, it appears probable that helium is a constituent of many mine gases.

One of the first exhaustive studies of mine gases was made in 1896 by Schloesing,[82] who discovered the presence of argon in the fire damp of French coal mines. In 1911 Moureu and Lepape[83] examined gas from the same mines and determined the proportions of helium, xenon, neon, krypton, and argon. The mutual proportions of the rare gases were found to approximate their proportions in the atmosphere (see p. 16), but the helium varied greatly, as shown in the following table:

Composition of coal gases.

	Liévin, France.	Anzin, France.	Lens, France.	Mons, Belgium.	Frankenholz, Palatinate.
Carbon dioxide	0 5	0.16	0.0	Trace.	2.80
Hydrocarbons	97.03	97.92	98.15	99.60	95.09
Nitrogen	2.41	1.85	1.81	.32	2.06
Argon, with traces of krypton and xenon	.04	.021	.0367	.003	.021
Helium, with traces of neon	.013	.044	.0003	.050	.027

Although the percentages of helium in these gases are small, the total volumes involved are considerable; according to the authors, the mine at Anzin emits about 4,380 cubic meters a year, and that at Frankenholz 3,650. cubic meters a year. In order to ascertain whether or not the helium is a direct product of radioactivity, Moureu and Lepape then tested the gases for radium emanation but found that they were not measurably radioactive. Examination of the radium and thorium content of the coal itself yielded the following results:[84]

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[78] Jaquerod, A., and Perrot, F. L., Sur l'emploi de l'hélium comme substance thermométrique et sur sa diffusion à travers la silice: Compt. Rend., vol. 139, p. 789, 1904.

[79] Piutti, Arnaldo, Absorption of helium by rocks and minerals [abstract]: Chem. Soc. Jour., vol. 100, pt. 2, p. 88, 1911.

[80] Holmes, Arthur, The association of lead with uranium in rock minerals and its application to the measurement of geologic time: Roy. Soc. London Proc., ser. A, vol. 85, p. 248, 1911; Radioactivity and the measurement of geologic time: Geologists Assoc. Proc., vol. 26, pt. 5, p. 289, 1915. Barrell, Joseph, Rhythms and the measurement of geologic time; Geol. Soc. America Bull., vol. 28, p. 745, 1917. For criticisms of this method, see Becker, G. F., Relations of radioactivity to cosmogony and geology: Geol. Soc. America Bull., vol. 19, p. 134, 1908; Isostasy and radioactivity: Idem, vol. 26, p. 171, 1915. Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, pp. 312-315, 1920.

[81] For compilations of analyses of mine gases, see Cady, H. P., and McFarland, D. F., The composition of natural gas, with special study of the constituents of Kansas gases: Kansas Univ. Geol. Survey, vol. 9, p. 286, 1908. Darton, N. H., Occurrence of explosive gases in coal mines: Bur. Mines Bull. 72, 1915.

[82] Schloesing, Th., fils, Sur la composition du grisou: Compt. Rend., vol. 122, p. 398, 1896; Étude sur l'azote et l'argon du grisou: Idem, vol. 123, p. 233, 1896.

[83] Moureu, Charles, and Lepape, A., Les gas rares des grisous: Compt. Rend., vol. 153, p. 847, 1911.

Relation between helium content of gas and radioactivity of coal.

	Liévin.	Anzin.	Lens.	Mons.	Frankenholz.
Helium (with traces of neon) in gas.....per cent..	0.013	0.044	0.0003	0.050	0.027
Radium in coal.......grams 10^{-12} per gram of coal..	$<$.02	$\leqq$.01	.97	.04	$<$.01
Thorium in coal......grams 10^{-5} per gram of coal..	....	$\leqq$.01	.33	.03	.02

It will be noted at once that the proportion of helium in the gas bears no relation to the proportions of radium and thorium in the coal. The Lens coal is by far the most radioactive, and the Lens gas is by far the poorest in helium, in fact, the arrangement of the coals in order of radioactivity is almost exactly the reverse of the arrangement of the gases in order of helium content. The authors cited calculate that the helium emitted by the Frankenholz mine in the last 20 years represents all that would be generated by 33,000,000,000 tons of such coal in a period of 100,000,000 years. As there is undoubtedly a great deal more helium still occluded in the unmined coal, they conclude that only a small part of the helium is being generated directly by radioactive processes and that most of it is fossil helium.

In a salt mine at Leopoldshall, near Stassfurt, a flow of combustible gas was encountered which according to Erdmann[85] proved to have the following composition:

Hydrogen..........................	83.6
Methane............................	4.4
Nitrogen and argon..................	11.8
Helium, with some neon.............	.17

This gas had been flowing for four and a half years, and during that time, it is calculated, 12 cubic meters of helium had escaped. In Erdmann's opinion the helium is generated by the decay of a local deposit of radium in the salt mass and is not an indication of the radioactivity of potassium.

The gas escaping in the Elkton mine, Cripple Creek, Colo., contains 76.8 per cent of nitrogen and 1.5 per cent of argon, but spectroscopic examination of the argon residue apparently failed to disclose the presence of helium.[86]

In this connection may be considered some analyses of gases of a somewhat different type, the gases accumulating in the tunnels or drifts at the mineral springs of Baden. The helium content and radioactivity of these gases, as determined by Sieveking and Lautenschläger,[87] are as follows:

Helium content and radioactivity of the Stollengase of Baden.

	Helium (per cent).	Activity (voltstunden).
Kirchenstollen, Baden-Baden.......	0.015	3,200
Murquellstollen, Baden-Baden.......	.004	2,000
Markgrafenstollen, Badenweiler.....	.004	900
Büttquellenstollen, Baden-Baden....	.003	4,770
Hauptstollen, Baden-Baden..........	.001	470
Ursprungstollen, Baden-Baden......	.001	459
Deckershof.........................	.0002	500

It will be noted that the helium content of these gases appears to bear a vague relation to their radioactivity, though the most active gas stands fourth in order of helium content.

HELIUM IN THE GASES OF MINERAL SPRINGS.

Within a few months after helium was discovered it was identified by Kayser[88] in the gas emitted by the springs at Wildbad, in the Black Forest, and in the course of the same year its presence in the springs at Cauterets, in the Pyrenees, was announced by Bouchard and by Kellas and Ramsay. Since that time helium has been detected in the gases of a great many European mineral springs, some of which emit several thousand liters of helium yearly.

By far the most extensive investigations of the occurrence of the rare elements in mineral-spring gases are those of Moureu and his collaborators, who found that the proportions of argon, krypton, and xenon in all gases approximate their proportions in the atmosphere, whereas the percentages of helium are very irregular. (See p. 16.) In order to investigate the relation between helium and radioactivity Moureu determined the radium emanation in a great many gases but found that no direct relation exists, except in so far as all the gases examined contain at least traces of both helium and the radio-elements. This is clearly brought out in the following table, which presents a summary of numerous papers by Moureu:[89]

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[84] Moureu, Charles, and Lepape, A., Hélium des grisous et radioactivité des houilles: Compt. Rend., vol. 158, p. 598, 1914.

[85] Erdmann, Ernst, Über heliumhaltige Gase der deutschen Kalilager: Deutsche chem. Gesell. Ber., vol. 43, pt. 1, p. 777, 1910.

[86] Lindgren, Waldemar, and Ransome, F. L., Geology and gold deposits of the Cripple Creek district, Colo.: U. S. Geol. Survey Prof. Paper 54, pp. 252-270, 1906.

[87] Sieveking, H., and Lautenschläger, L., Über Helium in Thermalquellen und Erdgasen: Physikal. Zeitschr., vol. 13, pt. 2, p. 1043, 1912.

[88] Kayser, H., Note on helium and argon: Chem. News, vol. 72, p. 99, Aug. 23, 1895.

Helium content and radioactivity of the gases of mineral springs.

[After Moureu. Localities in France except as otherwise noted.]

Locality.	Spring.	Constituents of gas (per cent).						Radium emanation (milligram-minutes per 10 liters).
		Carbon dioxide.	Oxygen.	Combustible gas.	Nitrogen.	Argon.	Helium.	
Aix-les-Bains	Soufre	4.00	0.0	Trace.	94.79	1.18	0.03	(a)
Do	Alun	(a)	(a)	(a)	(a)	1.153	.037	3.52
Aix-les-Thermes	Viguerie	.0	.0	0.0	98.45	1.453	.097	2.32
Badgastein, Austria	Gratenbüker	Trace.	1.40 (?)	(a)	97.25	1.181	.169	79.2
Bagnères-de-Bigorre	Salies	3.14	Trace.	(a)	95.49	1.322	.048	2.32
Bagnères-de-Luchon	Bordeu No. 1	.33	.0	(a)	98.275	1.306	.089	18.36
Do	Bordeu No. 2	.85	.0	1.30	96.45	1.25	.15	14.43
Do	Ferras	.0	Trace.	2.40	96.085	1.23	.285	4.19
Do	Pré No. 1	Trace.	.0	6.0	92.40	1.316	.284	10.23
Do	Saule No. 2	Trace.	.0	3.58	94.826	1.271	.323	9.42
Bains-les-Bains	Savonneuse	Trace.	4.69 (?)	.0	94.07	1.042	.198	3.52
Bourbon-l'Archambault	Thermal	49.81	.2	Trace.	48.96	.45	.58	.17
Bourbon-Lancy	Lymbe	2.8	2.2 (?)	(a)	91.96	1.20	1.84	2.06
Do	Reine	Trace.	.9 (?)	.0	96.1	1.15	1.75	(a)
Bussang	Demoiselles	82.71	Trace.	Trace.	16.72	.242	.328	(a)
Caldellas, Portugal	Carvalho	.0	2.44 (?)	(a)	96.40	1.143	.017	3.64
Cambo		.0	.76 (?)	(a)	98.49	(a)	(a)	(a)
Cauterets	Bois Vieux	Trace.	Trace.	(a)	98.48	1.418	.102	< .66
Do	César	Trace.	.0	.0	98.55	1.275	.165	< .66
Do	Mauhourat	.0	.0	(a)	98.47	1.49	.04	< .66
Do	Des Œufs	.60	Trace.	(a)	97.76	1.581	.059	< .66
Do	Raillère	.0	.0	Trace.	98.508	1.377	.115	< .66
Châtel-Guyon	Gubler	97.4	.54 (?)	(a)	2.036	.02337	.00063	< .20
Dax	Nehe	1.3	1.0	(a)	96.26	1.2226	.0174	.56
Do	Trou des Pauvres	1.9	.7	.0	96.20	1.195	.005	(a)
Eaux-Bonnes	Vieille	.0	.0	(a)	98.28	1.157	.563	< .66
Eaux-Chaudes	Esquirette	.0	.0	(a)	98.57	1.29	.140	< .66
Grisy	Ys	1.15	.0	Trace.	95.5	1.18	2.18	3.38
Do	No. 2	2.7	7.5 (?)	Trace.	88.77	1.02588	.00412	4.415
La Bourboule	Choussy	94.5	Trace.	.05	5.34	.10	.01	22
La Chaldette		2.75	.0	Trace.	95.17	1.31	.77	12.8
Lamalou	Usclade	99.5	(a)	(a)	(a)	(a)	(a)	< .66
Longwy	Des Récollets	.5	.0	Trace.	98.12	1.3654	.0146	< .1
Luxeuil	Bain-des-Dames	.83	Trace.	(a)	97.15	1.28	.74	1.24
Do	Grand Bain	1.6	.0	.0	96.36	1.305	.735	.50
Maizières	Romaine	1.7	.0	(a)	91.46	.92	5.92	1.48
Mont-Doré	Des Chanteurs	99.39	.168 (?)	(a)	.436	(a)	(a)	< .66
Nancy	Parc Sainte-Marie	1.75	.0	.0	95.36	1.29	1.60	.46
Néris	César	11.86	.0	(a)	86.29	.88	.97	.92
Ogeu	Peyré	Trace.	11.0	(a)	87.92	(a)	(a)	< .66
Panticosa, Spain	St.-Augustin	.2	1.6	(a)	97	(a)	(b)	(a)
Plombières	Crucifix	Trace.	3.30 (?)	.0	95.14	1.369	.201	(a)
Do	Des Capucins	1.0	8.90 (?)	(a)	88.65	1.414	.036	4.62
Do	Vauquelin	Trace.	Trace.	(a)	98.15	1.643	.207	11.8
Do	No. 3	Trace.	4.0	(a)	94.505	1.375	.120	10.74
Do	No. 5	1.58	1.47 (?)	.0	95.32	1.547	.104	6.16
Pougues-Saint-Léger		98.6	(a)	.0	(a)	.013	.002	< .20
Royat	César	99.5	.102 (?)	(a)	.393	(a)	(b)	< .66
St.-Honoré	Crevasse	2.20	.0	(a)	95.76	1.147	.893	< .20
Salins-Moutiers		41.50	Trace.	(a)	57.83	.446	.224	.66
Santenay (Côte-d'Or)	Lithium						10.16	
Do	Carnot						9.97	
Do	Fontaine Salée						8.40	
Spa, Belgium	Tonnelet	84.25	.175	(a)	15.296	.215	.064	< .20
Uriage		4.15	Trace.	Trace.	93.98	.938	.932	.147
Vichy	Des Célestins	84.5	.05	(a)	15.07	.302	.123	.216
Do	Chomel	99.834	Trace.	(a)	.162	.0027	.0015	.560
Do	Grande Grille	99.47	.00008	(a)	.51	.0172	.0018	.041
Do	Hôpital	98.65	.152	(a)	1.20	(a)	(a)	.019
Do	Mesdames	98.2	.08	(a)	1.72	(a)	(a)	.105

[a] Not determined.

[b] Not sought for.

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[89] Moureu, Charles, Recherches sur les gaz rares des sources thermales: Soc. chim. France Bull. 9, 4th ser., xxv pp., 1911.

Moureu points out the total lack of proportionality between radioactivity and the helium content of these gases and concludes that only a small fraction of the helium is now being generated by the decay of radium and that the greater part is fossil helium. As shown in the following table the volume of helium given off annually by some of the richer springs is considerable; Moureu calculates, for example, that the output of the Carnot Spring, at Santenay, represents all the helium that would be given off in a year by 91 tons of radium, or by 500,000,000 tons of pitchblende or thorianite. It is very evident, therefore, that the helium of these springs is not being generated by radioactivity as fast as it is being emitted, and that it represents the leakage from a great store of underground helium, which may have been generated during geologic time by the radio-elements or may represent primordial helium that has had no connection with radioactivity.

Volumes of helium emitted annually by some of the richer French mineral springs. [a]

Spring and locality.	Helium in gas (per cent).	Volume of helium per year.	
		Liters.	Cubic feet.
Lithium (Santenay, Côte-d'Or)	10.16	5,182	183
Carnot (Santenay, Côte-d'Or)	9.97	17,845	631
Fontaine Salée (Santenay, Côte-d'Or)	8.40	....	......
Romaine (Maizières, Côte-d'Or)	5.92	1,080	38
Ys (Grisy, Saône-et-Loire)	2.18	....	......
Lymbe (Bourbon-Lancy, Saône-et-Loire)	1.84	10,074	356
César (Néris, Allier)	.97	33,990	1,200
Choussy (La Bourboule, Puy-de-Dôme)	.01	3,048	108

[a] Moureu, Charles, and Lepape, A., Sur quelques mélanges gazeux naturels particulièrement riches en hélium; Gisements d'hélium: Compt. Rend. vol. 155, p. 197, 1912.

All these springs, except that at La Bourboule, lie in a comparatively narrow belt extending from Moulins, in Allier, northeastward to Vesoul, in Haute-Saône; and in this belt also there are several other springs which furnish gas containing more than 0.5 per cent helium, such as those at Luxeuil, St. Honoré, and Bourbon-l'Archambault. This areal distribution of the helium probably has a significance which special geologic examinations might disclose, but the surface geology of this region, as shown on the geologic map of France, suggests no explanation.

Although a few of the helium-bearing spring gases cited in the foregoing tables consist chiefly of carbon dioxide, a great majority are rich in nitrogen, resembling in this respect the helium-bearing natural gases of the United States. The general occurrence of helium in nitrogen-rich spring gases is shown in the following table, which has been compiled from a number of papers:

Helium and argon in the gases of mineral springs.

Locality.	Nitrogen (per cent).	Argon (per cent).	Helium (per cent).
1. Cauterets, Pyrenees, France	......	Present.	Present.
2. Bagnole de l'Orne, France	90.5	4.5	Trace.
3. Perchtoldsdorf, near Wien, Austria	93.6	1.04–1.11	....
4. Vöslau, near Wien, Austria	91.0	1.18–1.26	....
5. Allhusen well, Middleborough, England	......	.4	0.0
6. Well, Middleborough, England	......	.5	.0
7. Sulphur well, Harrogate, England	......	Present.	.0
8. Reykjavik, Iceland	......	1.14	.0
9. Bordeu à Luchon, France	96.22	2.56	.0
10. Karlsbad, Bohemia	.40	.38	
11. Wiesbaden, Germany	......	....	Present.
12. Gastein, Austria	......	1.29	.64
13. Uriage, Isère, France	93.98	.94	.93
14. La Aliseda, Spain	92.6	1.07	....
15. Bath, England	95.3	.74	.03
16. Wildbad, Black Forest, Germany	97	Present.	.8
17. Baden-Baden, Germany	......	....	.71

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2. Bouchard, Charles, Sur la composition des gaz qui se dégagent des eaux minérales de Bagnole de l'Orne: Idem, vol. 123, p. 969, 1896.

3. Bamberger, Max, Über den Nachweis von Argon in dem Gase einer Quelle in Perchtoldsdorf bei Wien: Monatsh. Chemie, Band 17, p. 604, 1896.

4. Bamberger, M., and Landsiedl, A., Über den Nachweis von Argon in den Badequellen von Vöslau bei Wien: Idem, vol. 19, p. 114, 1898.

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7. Ramsay, William, and Travers, M. W., The gaseous constituents of certain mineral substances and waters: Roy. Soc. London Proc., vol. 60, p. 442, 1897.

9. Moissan, Henri, Sur la présence de l'argon dans les gaz de la source Bordeu à Luchon et sur la présence du soufre libre dans l'eau sulfureuse de la grotte et dans les vapeurs de humage: Compt. Rend., vol. 135, p. 1278, 1902.

10. Pesendorfer, F., Zusammensetzung des dem Karlsbad Sprudel entströmenden Gases: Chem. Zeitung, vol. 29, p. 359, 1905.

11. Henrich, Ferd., Untersuchungen über die Thermalquellen von Wiesbaden und deren Radioaktivität: Physikal. Zeitschr., vol. 8, p. 112, 1907.

12. Ewers, P., Über das Vorkommen von Argon und Helium in den Gasteiner Thermalquellen: Physikal. Zeitschr., vol. 7, p. 225, 1906.

13. Massol, M. G., Sur la composition chimique des gaz spontanés de la source thermo-minérale d'Uriage (Isère): Compt. Rend., vol. 151, p. 1124, 1910.

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15. Ramsay, William, Report on the mineral waters of Bath: Chem News, vol. 105, p. 133, 1912.

16, 17. Sieveking, H., and Lautenschläger, L., Über Helium in Thermalquellen und Erdgasen: Physikal. Zeitschr., vol. 13, p. 1043, 192.

An examination of sea water and of the water of the Seine for helium was made by Troost and Ouvrard,[90] who report that it is present only in the faintest traces.

HELIUM IN VOLCANIC AND FUMAROLE GASES.

Unfortunately the earlier classic researches on the composition of volcanic gases—those of Bunsen, Deville and Leblanc, and Fouqué—were made before helium was discovered, and as most of the recent investigations deal only with the more abundant constituents of volcanic emanations, the available data on the distribution of helium in such gases are meager.

The presence of helium in Italian fumarole gases was established in 1898 by Nasini, Anderlini, and Salvadori, who found 0.014 per cent of helium in the gas emitted by the boric acid soffione of Larderello (Tuscany), and a smaller proportion in the gas of Monte Irone, Abano.[91] The same authors later detected helium in the gas of the solfatara of Pozzuoli (Campi Flegrei, near Naples) and in several other Vesuvius gases, as well as in the hydrocarbon gases of Salsomaggiore and Bagni della Poretta, in northern Italy.[92] The following table shows some of the analyses made by these authors, as well as a later analysis of the Larderello gas made by Porlezza and Norzi,[93] and an analysis of Vesuvius gas by Gautier:[94]

Analyses of gases of Italian fumaroles.

[Per cent.]

	1	2	3	4	5
Hydrogen sulphide	2.070	2.000	2.0000	1.13	....
Carbon dioxide	92.800	92.000	92.2000	10.73	96.52
Hydrogen	2.600	2.400	2.4500	....	.015
Methane	1.400	1.900	1.7800	12.00	.12
Oxygen	.050	.200	.1800	.40	.46
Nitrogen	1.048	1.455	1.3500	74.23	2.87
Argon	.021	.029	.0245	1.51	.028
Helium	.010	.014	.0155		
	•99.999	99.998	100.0000	100.00	100.013

1–2. Gas from different parts of the boric acid soffione of Larderello. Analysis by Nasini, Anderlini, and Salvadori.
3. Same. Later analysis by Porlezza and Norzi.
4. Gas from boiling spring at Monte Irone, Abano. Analysis by Nasini, Anderlini, and Salvadori.
5. Gas from old fumarole at Agnano, near Naples, representing Vesuvius gas. Analysis by A. Gautier; helium determined by Charles Moureu.

The gases emitted by the boiling springs of Iceland, which are indirect manifestations of volcanic activity, have been investigated by Thorkelsson,[95] from whose valuable paper the following analyses are cited:

Analyses of gas emitted by the hot springs of Iceland.

[Per cent.]

Spring.	H_2S.	CO_2.	H_2.	CH_4.	O_2.	N_2.	A.	He.
Reykir No. 5	....	....	....	....	....	98.34	1.61	0.0146
Hveravellir No. 2	2.8	79.5	....	0.9	....	16.5	.294	.0050
Hveravellir No. 25	....	77.8	....	1.0	0.2	20.6	.441	.0063
Graffarbakki No. 1	....	6.4	....	.8	1.1	90.0	1.68	.0104
Laugarás No. 1	....	....	....	.7	....	97.4	1.93	.0104
Reykjafoss No. 1	....	27.0	2.5	.2	.0	67.9	1.36	.0103
Hengill No. 1	11.0	73.4	13.5	.3	....	1.8	.011	.0006
Hengill No. 3	11.2	67.0	17.2	.6	....	3.9	.088	.0020

Moissan[96] examined several samples of gas from the fumaroles of Mont Pelée, Martinique, but reported no helium in one sample and apparently did not look for it in the others. Grossman,[97] however, found traces of helium in the gas contained in lava from Mont Pelée, but none in several lavas from Vesuvius and other localities. Day and Shepherd[98] state that the gases of Kilauea examined by them contain no helium, argon, or other rare gases.

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[90] Troost, L., and Ouvrard, L., Sur l'origine de l'argon et de l'hélium dans les gaz dégagés par certaines eaux sulfureuses: Compt. Rend., vol. 121, p. 798, 1895.

[91] Nasini, R., Anderlini, F., and Salvadori, R., Ricerche sulle emanazioni terrestre italiane: Gazz. chim. ital., vol. 28, pp. 81–153, 1898.

[92] Idem, vol. 36, pt. 1, p. 429, 1906.

[93] Porlezza, C., and Norzi, G., Nuovi studi sui gas dei soffione boraciferi di Larderello: R. Accad. Lincei Atti, 5th ser., vol. 20, pt. 2, p. 338, 1911.

[94] Gautier, Armand, Observations sur la nature et l'origine des gaz qui forment les fumerolles volcaniques ou qui sortent des cratères des anciens volcans: Compt. Rend., vol. 149, p. 84, 1909.

[95] Thorkelsson, Thorkell, The hot springs of Iceland: Acad. roy. sci. et let. Danemark Mém., 7th ser., vol. 8, pp. 181–264, 1910.

[96] Moissan, Henri, Sur la présence de l'argon, de l'oxyde de carbone et des carbures d'hydrogène dans les gaz des fumerolles du Mont Pelé à la Martinique: Compt. Rend., vol. 135, p. 1085, 1902.

HELIUM IN THE ATMOSPHERE.

According to the latest determination by Sir William Ramsay[99] the atmosphere near the earth's surface contains 1 part of helium in 245,300 parts by volume, or about 0.0004 per cent. This is the figure generally accepted, though according to Claude[1] the percentage is 0.0005. Joly[2] has calculated that the atmosphere up to a height of 8 kilometers contains, if homogeneous, 16×10^{14} cubic meters of helium.

Although there are a few experimental data on the composition of the air several miles above the earth, it is generally believed that the atmosphere consists of two layers—an inner adiabatic layer 8 or 10 kilometers high, which is practically homogeneous in composition, and an outer and much thicker isothermal layer, or layer in which the temperature is uniform and constant and in which the distribution of the gases is controlled by gravity. The theoretical proportions of the several gases at various levels in the upper atmosphere have been calculated roughly by Jeans[3] and are given in the following table:

Proportions of the atmospheric gases at various levels in the upper atmosphere.

[The base of the upper atmosphere is taken at 10.5 kilometers above the earth's surface.]

Gas.	Molecular weight.	Number of molecules per cubic centimeter at height z (in kilometers).				
		$z=0$	$z=20$	$z=80$	$z=160$	$z=800$
Hydrogen	2	10×10^{13}	8×10^{13}	430×10^{11}	182×10^{11}	3×10^{10}
Helium	4	4×10^{13}	2.6×10^{13}	73×10^{11}	13×10^{11}	10^{6}
Neon	20	12.5×10^{13}	1.4×10^{13}	0.3×10^{11}	0.5×10^{7}	0
Nitrogen	28	$780,600\times10^{13}$	$42,900\times10^{13}$	520×10^{11}	35×10^{7}	0
Oxygen	32	$210,000\times10^{13}$	$7,000\times10^{13}$	25×10^{11}	0.3×10^{7}	0
Argon	40	$9,400\times10^{13}$	139×10^{13}	0.04×10^{11}	10^{2}	0
Krypton	83	0.5×10^{13}	10^{9}	0	0	0
Xenon	130	0.06×10^{13}	10^{5}	0	0	0
		1×10^{19}	5×10^{17}	1×10^{14}	2×10^{13}	3×10^{10}

At a height of 80 kilometers (50 miles) some of the heavier gases disappear entirely, and helium, instead of being the sixth constituent in order of abundance, is outranked only by hydrogen and nitrogen. At a height of 160 kilometers (100 miles) the atmosphere consists chiefly of hydrogen and helium, the other constituents being present only in small proportions.

C. E. Van Orstrand has constructed a curve from the foregoing figures and has computed the relative volumes of helium in the concentric zones of the atmosphere, as follows:

Proportions of helium in the atmosphere at different levels above the earth's surface.

[Number of molecules per cubic centimeter at earth's surface, 2.75×10^{19}.]

Height (kilometers).	Helium (molecules $\times10^{16}$ per cubic centimeter).	Height (kilometers).	Helium (molecules $\times10^{16}$ per cubic centimeter).
0- 2	2,000	16-18	620
2- 4	1,600	18-30	3,360
4- 6	1,280	30-90	9,990
6- 8	1,040	90-170	3,440
8-10	870	170-870	4,550
10-12	760		
12-14	700		30,870
14-16	660		

From this figure Mr. Van Orstrand calculates that the total mass of helium in the atmosphere up to 870 kilometers is $11,456 \times 10^6$ tons, which is equivalent to a total volume, at standard temperature and pressure, of about $58,186 \times 10^9$ cubic meters.

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[97] Grossman, M., Analyse quantitative des gaz occlus dans les laves des dernières éruptions de la Montagne Pelée et du Vésuve: Compt. Rend., vol. 148, p. 991, 1909.

[98] Day, A. L., and Shepherd, E. S., Water and volcanic activity: Geol. Soc. America Bull., vol. 24, p. 573, 1913.

[99] Ramsay, William, The gases of the atmosphere, 4th ed., p. 257, London, 1915.

[1] Claude, Georges, Sur la composition de l'air atmosphérique: Compt. Rend., vol. 148, p. 1454, 1909.

[2] Joly, J., Radioactivity and geology, p. 210, London, 1909.

[3] Jeans, J. H., The dynamical theory of gases, chap. 15, Cambridge, 1916. Earlier calculations have been given by James Dewar. (Problems of the atmosphere: Roy. Inst. Great Britain Proc., vol. 17, 1902-1904, p. 223) and by W. J. Humphreys (Distribution of gases in the atmosphere: Mount Weather Obs. Bull., vol. 2, p. 66, 1909).

It has been argued by Stoney[4] that hydrogen because of its lightness, ascends to the uppermost levels of the atmosphere, and thence in part escapes into space; and it has been suggested by both Ramsay[5] and Moureu[6] that the same theory may apply to helium as well. According to Jeans, however, the loss of hydrogen from the earth's atmosphere is at present so slow as to be negligible, and there can therefore be practically no loss of helium. A similar conclusion is reached by Bryan.[7]

COSMIC HELIUM.

The discovery of helium in the solar chromosphere in 1868 was followed by its identification in the spectra of a great many stars, and it is now recognized that helium is one of the most prominent of cosmic elements. Helium is abundant in the nebulae and is so prominent in the hotter stars of the Orion type that these are often designated the helium stars.

In contrast to helium, which is so prominent in the stars and nebulae, the radio-elements, so closely associated with helium on the earth, are conspicuous by their absence. Dyson has doubtfully reported the presence of radium in the solar chromosphere, and Giebeler believes that he has detected radium and its emanation in the spectrum of the new star Nova Geminorum 2, but despite the fact that radium is easily recognized spectroscopically, other observers have failed to confirm these results and report that radium is absent.[8] Similarly, uranium and thorium, so far as the writer can learn, have not been detected in any of the celestial bodies, though lead has been identified in the sun.

The prominence of helium and the absence of uranium and thorium in celestial bodies are explained by Becker's view[9] that uranium is to be regarded as the unstable compound $PbHe_8$ and thorium as the compound $PbHe_6$, which differ from other compounds chiefly in that their disintegration is spontaneous and proceeds at a fixed rate. As these compounds are very strongly endothermic, disintegrating with the evolution of heat, their formation must have been attended by the absorption of heat and therefore could have taken place only under conditions of great temperature and pressure. Similar arguments have been developed by Arrhenius and others.[10] If this view is accepted, the presence of helium and lead in the sun and the absence of their compounds, uranium and thorium, are explained. Furthermore, it follows that if helium and lead combine only under certain conditions there is in all probability a great deal of helium in the earth which has never entered into this combination and has had no connection with radioactivity and which may thus be regarded as true primordial helium.

INFERRED HELIUM.

THE MEASUREMENT OF RADIOACTIVITY.

In addition to the direct data on the distribution of helium reviewed in the foregoing pages, it is evident that, as helium is formed in the decay of the radio-elements, each occurrence of radioactive material connotes the presence of helium. Early recognition of the extraordinary qualities of radium and of its geochemical significance and therapeutic value led to the making of extensive surveys of the distribution of radioactive materials in the earth's crust, and the data so gathered thus have an indirect bearing on the distribution of helium.

Almost inconceivably minute quantities of radium and its products may be accurately measured by taking advantage of the fact that the rays emitted by these substances have the property of ionizing the surrounding gases and so making them carriers of electricity. The extent of this ionization is measured by means of the electroscope, which is designed to permit accurate observation of the rate of loss of potential of a charged insulated strip of gold leaf exposed to a definite volume of air containing the emanation. As each alpha ray emitted gives rise to many thousand ions per second, it is evident that measurements made in this way are incomparably more refined than those obtainable by the most delicate chemical balance or even by the spectroscope. Exceedingly small quantities of helium may be recognized in a spectroscope, but far smaller quantities of the elements that give rise to helium may be measured electrically.

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[4] Stoney, Johnstone, Chem. News, vol. 71, p. 67, 1895.

[5] Ramsay, William, op. cit., p. 265.

[6] Moureu, Charles, Les gaz thermaux: Rev. sci., 1914, p. 65.

[7] Bryan, G. H., The kinetic theory of planetary atmospheres: Roy. Soc. London Philos. Trans., vol. 196, p. 1, 1900.

[8] Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, p. 312, 1920.

[9] Becker, G. F., Relations of radioactivity to cosmogony and geology: Geol. Soc. America Bull., vol. 19, p. 113, 1908.

[10] See Becker, G. F., Isostasy and radioactivity: Geol. Soc. America Bull., vol. 26, p. 194, 1915.

In practice sufficient time must of course be allowed to permit the attainment of equilibrium. If a rock is to be tested, it is first brought into solution and allowed to stand until the maximum quantity of emanation has accumulated—that is, until the rate of decay is equal to the rate of production. The gases are then removed by boiling and introduced into the electroscope, and the measurement of their ionizing power is easily recalculated into terms of radium itself.

DISTRIBUTION OF THE RADIO-ELEMENTS.

A great many determinations of radium in minerals, soils, rocks, and spring waters and in the ocean and atmosphere have been made, but as their bearing on the distribution of helium is indirect only a few representative measurements will be given here.

Measurements of the radioactivity of a number of minerals, made in connection with determinations of their helium content, have been given on pages 44–45. It will be noted that many of the rare-earth minerals are rich in radium, as compared with ordinary rocks (discussed below), and that practically all the minerals tested contain some radium, though the silicates and the common metallic ore minerals are generally poor.

The wide distribution of the radio-elements in terrestrial materials was discovered in 1901 by Elster and Geitel, who observed that the air in cellars and caves is markedly radioactive and who thereupon tested a number of samples of soil and clay.[11] They found that most of the samples they examined were distinctly radioactive, and later investigations have confirmed their results. Moore,[12] for example, found the average emanation from 14 type soils in the United States to be equivalent to 1.97×10^{-12} grams of radium per gram of soil, and that of the subsoils to be equivalent to 1.52×10^{-12} grams.[13] The average thorium emanation of five soils was found to represent 4×10^{-5} grams of thorium per gram of soil. Sanderson[14] examined 13 Minnesota soils and found 1.3×10^{-13} to 8×10^{-13} grams of radium and 2.5×10^{-6} to 7.1×10^{-6} grams of thorium per cubic centimeter of soil.

The first systematic survey of the distribution of radium in rocks was made in 1906 by R. J. Strutt. His results (as corrected by Eve and McIntosh for the use of an erroneous constant) showed the average radium content of 28 igneous rocks from different parts of the world to be 1.7×10^{-12} per gram of rock and that of 17 sedimentary rocks to be 1.1×10^{-12} gram. Joly, who shortly afterward began a much more extensive survey, obtained results several times as large as Strutt's, the disparity being apparently due to the use of different methods of bringing the specimens into solution. As other investigators have obtained results approximating Strutt's, and as Joly's recent determinations are considerably lower than his earlier ones, it seems probable that most of the earlier results should be rejected.

The accompanying table shows the average radium content of groups of comparable rocks from all over the world, as determined by several investigators. Most of Joly's earlier determinations have been omitted. Although future work will undoubtedly modify the mean values somewhat, a sufficient number of determinations have now been made to permit a fair estimate of the radium content of the earth's surface rocks.

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[11] Elster, J., and Geitel, H., Sur la radioactivité de l'atmosphère et du sol: Arch. sci. phys. nat., 4th ser., vol. 17, p. 13, 1904. Determinations of the radioactivity of many minerals, rocks, spring waters, etc., were made prior to 1905, but the results were commonly expressed in arbitrary units and have little value for comparison. A good review of the work to 1905, with bibliography, is given by Georg v. d. Borne (Die radioaktiven Mineralien, Gesteine und Quellen: Jahrb. Radioaktivität u. Electronik, Band 2, Heft 1, p. 77, 1905).

[12] Moore, R. B., The radioactivity of some type soils of the United States: Jour. Ind. and Eng. Chemistry, vol. 6, p. 370, 1914.

[13] 1.52×10^{-12} grams per gram equals one hundred and fifty-two trillionths of 1 per cent. The radium content of ordinary natural substances is of this order of magnitude.

[14] Sanderson, J. C., Radioactive content of certain Minnesota soils: Am. Jour. Sci., 4th ser., vol. 39, p. 391, 1915.

Radium content of rocks.

Rock.	Locality.	Number of specimens.	Radium (grams × 10^{-12} per gram of rock).	Equivalent value of uranium (grams × 10^{-5}).	Observer.
Igneous rocks:					
Granites and syenites	Various	10	3.33		Strutt.[a]
Granites and porphyries	Sub-Antarctic islands	7	2.1		Farr and Florance.[b]
Granites (Archean)	Mysore, India	16	1.5		Smeeth and Watson.[c]
Rhyolites	Yellowstone Park, U. S. A.	4	2.3		Schlundt and Moore.[d]
Obsidian	do	2	1.9		Do.[d]
Nephelite rocks	Montreal, Canada	4	2.16		Eve and McIntosh.[e]
Recent volcanic rocks	Various	12	7.1		Joly.[f]
Various types	Sumatra	10	1.6		Büchner.[g]
Various types	Borneo	17	1.7		Do.[h]
Diorites and similar rocks	Various	7	1.16		Strutt.[a]
Basic rocks	do	11	.53		Do.[a]
Basalts	The Deccan, India	6	4.3		Joly.[f]
Basic rocks (Archean)	Mysore, India	21	.24		Smeeth and Watson.[c]
Basalts	England	4	.37		Strutt.[i]
Acidic rocks (composite sample).	Various	86	3.01		Joly.[j]
Intermediate rocks (composite sample).	do	48	2.57		Do.[j]
Basic rocks (composite sample).	do	31	1.28		Do.[j]
		296	2.3	0.7	
Metamorphic rocks:					
Schist and gneiss	Scotland	3	5.7		Joly.[f]
Gneiss (composite sample)	Various	14	2.1		Do.[j]
Schists (sedimentary)	do	9	1.1		Fletcher.[k]
Quartzite	Dublin	2	.7		Do.[k]
Quartzite and graywacke	Various	9	1.5		Do.[k]
Slates and phyllites	do	16	1.3		Do.[k]
		53	1.7	0.5	
Sedimentary rocks:					
Sandstones (composite sample).	Various	39	1.5		Joly.[j]
Sandstones	do	24	1.5		Fletcher.[k]
Sandstones, slates, chalk, etc.	do	17	1.1		Strutt.[a]
Slates and shales (composite sample).	do	20	1.5		Joly.[j]
Sandstones and sandy shales.	Limburg	8	1.7		Büchner.[h]
Limestones and marbles	Europe	10	1.4		Do.[l]
Limestone, dolomite, chalk	Various	24	.8		Fletcher.[k]
		142	1.3	0.4	
Miscellaneous:					
Globigerina ooze	Atlantic and Pacific oceans	4	3.3		Joly.[j]
Radiolarian ooze	Central Pacific Ocean	2	13.1		Do.
Hot-spring deposits	Yellowstone Park, U. S. A.	29	2.9		Schlundt and Moore.[d]
Coal		1	0		Fletcher.[k]
Do	Northern France	5	< .23		Moureu and Lepape.[m]

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[a] Strutt, R. J., On the distribution of radium in the earth's crust and the earth's internal heat: Roy. Soc. London Proc., ser. A, vol. 77, p. 472, 1906; vol. 78, p. 150, 1906. For corrected results see Eve, A. S., and McIntosh, D., The amount of radium present in typical rocks in the immediate neighborhood of Montreal: Philos. Mag., 6th ser., vol. 14, p. 231, 1907.

[b] Farr, C. C., and Florance, D. C. H., On the radium content of certain igneous rocks from the Sub-Antarctic Islands of New Zealand: Philos. Mag., 6th ser., vol. 18, p. 812, 1909.

[c] Smeeth, W. F., and Watson, H. E., The radioactivity of Archean rocks from the Mysore State, India: Philos. Mag., 6th ser., vol. 35, p. 206, 1918.

[d] Schlundt, Herman, and Moore, R. B., Radioactivity of the thermal waters of Yellowstone National Park: U. S. Geol. Survey Bull. 395, pp. 25-26, 1909.

[e] Eve, A. S., and McIntosh, D., The amount of radium present in typical rocks in the immediate neighborhood of Montreal: Philos. Mag., 6th ser., vol. 14, p. 231, 1907.

[f] Joly, J., Radioactivity and geology, pp. 42-60, London, 1909.

[g] Büchner, E H., Investigations of the radium content of rocks: K. Akad. Weten. Amsterdam Proc., vol. 13, pt. 1, p. 359, 1910.

[h] Büchner, E.H., idem, vol. 14, pt. 2, p. 1063, 1912.

[i] Strutt, R. J. On the radium content of basalt: Roy. Soc. London Proc., ser. A., vol. 84, p. 377, 1910.

[j] Joly, J., The radioactivity of terrestrial surface materials: Philos. Mag., 6th ser., vol. 24, p. 694, 1912.

[k] Fletcher, A. L., On the radium content of secondary rocks: Philos. Mag., 6th ser., vol. 23, p. 279, 1912.

[l] Büchner, E. H., op. cit., vol. 13, pt. 2, p. 818, 1911.

[m] Moureu, C., and Lepape, A., Hélium des grisous et radioactivité des houilles: Compt. Rend., vol. 158, p. 598, 1914.

The figures given indicate that the igneous rocks are distinctly richer in radium than the sedimentary rocks, and that the metamorphosed varieties of both classes occupy, as would be expected, an intermediate position. Among the igneous rocks the acidic types are notably the richest, and the intensive studies of Smeeth and Watson in the Mysore State indicate that radium is distinctly subject to magmatic differentiation. Basic varieties are generally poor in radium, the only exceptions noted being the Deccan traps investigated by Joly. Among sedimentary rocks the limestones appear to be somewhat poorer than the sandstones and shales, though the difference is not marked. The deep-sea deposits examined by Joly are exceptionally rich in radium. Hot-spring deposits appear in general to be somewhat radioactive, though Schlundt and Moore point out that probably only radium is deposited by the waters, and as it is not sustained by uranium, as in normal rock, its activity soon decreases, and the amount remaining depends chiefly on the age of the deposit. The few specimens of coal examined are surprisingly low in radium. The average radium content of rocks is considerably higher than that of the soils already referred to, a fact which indicates that weathering plays an important part in reducing the radium content. In this connection Joly cites a determination of a sample of sand from the Arabian Desert which showed only 0.4×10^{-12} gram of radium.

The distribution of thorium in the earth's crust has until recently received little attention, and few data regarding it are available. The composite samples of igneous rocks made up by Joly and tested by him for radium have been examined for thorium by Poole, and these determinations, together with a number of others, are given in the accompanying table. In general the distribution of thorium is similar to that of radium; the acidic igneous rocks are richer than the basic, and the argillaceous sediments are richer than the sandstones and far richer than the limestones.

Thorium content of rocks.

Rock.	Locality.	Number of specimens.	Thorium (grams × 10^{-6} per gram of rock).	Observer.
Igneous rocks:				
Lavas, recent	Various	8	1.6	Joly.[a]
Granites, gneissic	St. Gothard tunnel	11	1.85	Do.[a]
Acidic rocks, composite	Various	86	2.05	Poole.[b]
Intermediate rocks, composite	do	48	1.64	Do.[b]
Basic rocks, composite	do	56	.56	Do.[b]
		209	1.5	
Metamorphic rocks:				
Schists	St. Gothard tunnel	21	1.18	Joly.[a]
Altered sediments	do	19	.77	Do.[a]
		40	1.0	
Sedimentary rocks:				
Calcareous rocks	Various	34	<.07	Joly.[c]
Sandstones	do	13	.54	Do.[c]
Argillaceous rocks	do	18	1.14	Do.[c]
		65	.5	

[a] Joly, J., On the distribution of thorium in the earth's surface materials: Philos. Mag., vol. 18, p. 140, 1909.
[b] Poole, J. H. J., The average thorium content of the earth's crust: Philos. Mag., vol. 29, p 483, 1915.
[c] Joly, J., The amount of thorium in sedimentary rocks: Philos. Mag., vol. 20, pp. 125, 353, 1910.

As thorium is the parent of its series, whereas radium is simply an intermediate member of the uranium series, the figures cited give little idea of the relative importance of the two groups of radio-elements. As the ratio of radium in equilibrium with uranium is 3.4×10^{-7}, the radium determinations may be calculated in terms of uranium and compared directly with the figures for thorium. The following table shows the thorium content of the four composite samples of igneous rocks determined by Poole and the uranium content of the same samples calculated from the radium values obtained by Joly:

Thorium and uranium content of igneous rock.

[Grams $\times 10^{-5}$ per gram of rock.]

	Thorium.	Uranium.
Granites and acidic intrusive and volcanic rocks (86)	2.05	0.88
Syenites, diorites, trachytes, and porphyries (48)	1.64	.78
Basalts, gabbros, diabases, and norites (56)	.56	.38
Lavas, Vesuvius (7)	2.36	3.70

Exclusive of the lavas, the average thorium content in the three groups is 1.42×10^{-5}, whereas the average uranium content is about half that figure, or 0.68×10^{-5}. If the general averages of all uranium and thorium determinations given in the tables on pages 55–56 are considered, the ratios are about the same. Computing the uranium values as before, we find (in grams $\times 10^{-5}$) for igneous rocks uranium and 1.5 of thorium; for metamorphic rocks 0.5 of uranium and 1.0 of thorium; and for sedimentary rocks 0.4 of uranium and 0.5 of thorium. The average thorium content of all rocks therefore appears to be about twice as great as the average uranium content, and it is very evident that thorium, which until recently was neglected entirely in geophysical calculations, must be taken into account.[15]

Determinations of the radioactivity of a great many spring waters have been made, chiefly in connection with therapeutic studies, but such measurements have little geochemical significance and only a few will be considered here. Ordinary springs of shallow ground water usually show only slight activity, but many hot springs or other deep-seated flows that are rich in the less common mineral 0.7 constituents are highly radioactive. The above table contains measurements of the activity of some well-known mineral springs

Radioactivity of mineral waters.

Source.	Location.	Radium (grams $\times 10^{-11}$). Per liter of water.	Radium (grams $\times 10^{-11}$). Per liter of gas.	Observer.
Imperial Spring	Hot Springs, Ark	[a] 904.4		Boltwood.[b]
Arsenic Spring	do	[a] 81.3		Do.[b]
Dripping Spring	do	[a] 27.2		Do.[b]
Sweet Springs	Sweet Springs, Mo	[a] 80.5		Moore and Schlundt.[c]
Hot River	Yellowstone Park	144.0		Schlundt and Moore.[d]
White Sulphur Spring	do	124.0	26.2	Do.[d]
Mushroom Pool	do	38.0	287.0	Do.[d]
Bench Spring	do	24.0	139.0	Do.[d]
Nymph Spring	do	26.3	7.3	Do.[d]
City well (deep)	Columbia, Mo	[a] 5.0		Do.[e]
King's well	Bath, England	13.9		Ramsay.[f]
Grabenbäckerquelle	Gastein, Austria	[g] 620.0	[g] 2,256.0	Mache.[h]
Eisenquelle	Karlsbad, Austria	[g] 188.0		Engler and Sieveking.[i]
Murquelle	Baden-Baden, Germany	[g] 96.0		Do.[i]
Waldquelle	Marienbad, Austria	[g] 18.3	[g] 43.6	Mache and Meyer.[j]
Vauquelin	Plombières, France	[g] 178.4	[g] 208.0	Curie and Laborde.[k]
D'Alun	Aix-les-Bains, France	[g] 224.0	[b] 64.0	Do.[k]
Yunokubo	Masutomi, Japan	9,001.2		Ishizu.[l]
Furo-sen	Beppa, Japan	6.6		Do.[l]

[a] Originally stated in terms of uranium.

[b] Boltwood, B. B., On the radioactive properties of the waters of the springs on the Hot Springs Reservation, Hot Springs, Ark.: Am. Jour. Sci., 4th ser., vol. 20, p. 128, 1905.

[c] Moore, R. B., and Schlundt, Herman, On the radioactivity of some natural waters of Missouri: Am. Electrochem. Soc. Trans., vol. 8, p. 291, 1905.

[d] Schlundt, Herman, and Moore, R. B., Radioactivity of the thermal waters of Yellowstone National Park: U. S. Geol. Survey Bull. 395, 1909.

[e] Schlundt, Herman, and Moore, R. B., Radioactivity of some deep well and mineral waters: Jour. Phys. Chem., vol. 9, p. 320, 1905.

[f] Ramsay, William, Report on the mineral waters of Bath: Chem. News, vol. 105, p. 133, 1912.

[g] Originally stated in terms of electrostatic (Mache) units; here recalculated by the use of the factor 1 gram radium $= 2.5 \times 10^{9}$ Mache units.

[h] Mache, H., Über die Radioaktivität der Gasteiner Thermen: K. Akad. Wiss. Wien Sitzungsber., vol. 113, Abt. 2 a, p. 1329, 1904.

[i] Engler, C., and Sieveking, H., Der Radioaktivität der Mineralquellen: Chem. Zeitung, vol. 31, p. 813, 1907.

[j] Mache, H., and Meyer, S., Über die Radioaktivität der Quellen der böhmischen Bädergruppe: K. Akad. Wiss. Wien Sitzungsber., vol. 114, Abt. 2 a, p. 355, 1905.

[k] Curie, P., and Laborde, A., Sur la radioactivité des gaz qui proviennent de l'eau des sources thermales: Compt. Rend., vol. 142, p. 1462, 1906.

[l] Ishizu, R., The mineral springs of Japan, p. 164, Tokyo, 1915.

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[15] Joly, J., The radioactivity of terrestrial surface materials: Philos. Mag., 6th ser., vol. 24, p. 694, 1912.

and suffices to show the average degree of activity of such flows.[16] The gas emitted by such springs is generally richer in radium emanation than the waters.[17]

The radioactivity of petroleum and natural gas has been investigated to some extent and is of particular interest in connection with the occurrence of helium in natural gas. The activity of petroleum was discovered by Burton,[18] who examined samples of oil from a well near Petrolia, Ontario, and his observations were soon confirmed by Himstedt[19] and by Elster and Geitel.[20] Burton concluded that the activity of the oil was due to radium products and suggested that the oil might also contain radium itself. This was denied by Engler,[21] who examined many samples of European oils and found that although most fresh samples are active, those which have been kept for some years show no activity, indicating that the effects are due to the emanation alone. Hurmuzescu[22] found the light oils of Rumania to be more active than the heavier ones. Himstedt observed that the emanation is much more soluble in crude oil than in water, and Boyle[23] found that radium emanation is about 50 times as soluble in refined petroleum oils as in water. Apparently, therefore, the activity of petroleum is due simply to its faculty of absorbing emanation from the surrounding rocks.

Unfortunately, most determinations of the radioactivity of oils are only qualitative or are expressed in arbitrary units, but the following are given in terms comparable to those used in the foregoing tables:

Radioactivity of oil and gas from the Nishiyama field, Japan.[a]

Well.	Radium (grams×10^{-12}).	
	Per liter of oil.	Per liter of gas.
R. 22, Takiya	166	35
R. 7, Nagamine	144	....

[a] Cited by Ishizu, R., The mineral springs of Japan, p. 189, Tokyo, 1915.

The radioactivity of natural gas was first observed by McLennan,[24] who tested a number of samples from the Welland and Brantford districts in western Ontario. Gas from the Niagara rocks, at a depth of 500 feet, was more active than any other examined, and gas from the Medina rocks at 900 feet ranked next to the Niagara gas. Samples from the Clinton sand at 750 feet were less active than those from the Medina, and the least active were those from the Trenton limestone at a depth of 3,000 feet. McLennan's observations seem to show an irregular but pronounced decrease in radioactivity with increase in depth, which may be significant in connection with the usual decrease in helium content with increase in depth, as described on pages 23–24. The radioactivity of a few samples of European natural gas, expressed in arbitrary units, is given on page 34.

The radioactivity of the atmosphere itself, which was first observed by Elster and Geitel, has been studied by many investigators.[25] It has been found that both radium and thorium emanation are present in the atmosphere, but that the amount differs in different localities and also varies greatly in relation to meteorologic conditions. In order to eliminate the meteorologic factors as far as possible and measure the emanation itself, Eve and Satterly used charcoal to absorb the emanation from a known quantity of air for a period of some hours or days, and Ashman condensed the emanation directly by means of liquid air. The results are as follows:

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[16] The papers cited in the table contain a great many more determinations than are here shown. Other measurements are given by Curie, Mme. P., Traité de radioactivité, vol. 2, p. 497, Paris, 1910; Sieveking and Lautenschläger, Über Helium in Thermalquellen und Erdgasen; Physikal. Zeitschr., vol. 13, pt. 2, p. 1043, 1912; Mache, H., and Meyer, S., Über die Radioactivität österreichischer Thermen: Physikal. Zeitschr., vol. 6, p. 692, 1905; Blanc, G. A., Radioactivity of mineral springs: Philos. Mag., 6th ser., vol. 9, p. 148, 1905; Batelli, A., Occhialini, A., and Chella, S., Untersuchungen über Radioaktivität: Physikal. Zeitschr., vol. 8, p. 65, 1907; Himstedt, F., Über die radioaktive Emanation der Wasser- und Ölquellen: Physikal. Zeitschr., vol. 5, p. 210, 1904; Henrich, F., Untersuchungen über die Thermalquellen von Wiesbaden und deren Radioaktivität: Physikal. Zeitschr., vol. 8, p. 112, 1907.

[17] See Schlundt, H., and Moore, R. B., Radioactivity of the thermal waters of Yellowstone National Park: U. S. Geol. Survey Bull. 395, 1909; Moureu, C., and Lepape, A., La radioactivité des sources thermales de Bagnères-de-Luchon: Compt. Rend., vol. 148, p. 834, 1909; Mache, H., and Meyer, S., op. cit.

[18] Burton, E. F., A radioactive gas from crude petroleum: Philos. Mag., 6th ser., vol. 8, p. 498, 1904; Über ein aus Rohpetroleum gewonnenes radioaktives Gas: Physikal. Zeitschr., vol. 5, p. 511, 1904.

[19] Himstedt, F., Über die radioaktive Emanation der Wasser- und Ölquellen: Annalen der Physik, 4th ser., vol. 13, p. 573, 1904; Physikal. Zeitschr., vol. 5, p. 210, 1904.

[20] Elster, J., and Geitel, H., Sur la radioactivité de l'atmosphère et du sol: Arch. sci. phys. nat., 4th ser., vol. 17, p. 13, 1904.

[21] Engler, C., Beiträge zur Chemie und Physik der Erdölbildung: Petroleum Zeitschr., vol. 2, p. 849, 1907.

[22] Hurmuzescu, Dragomir, Sur la radioactivité du pétrole: Cong. internat. pétrole, Bucharest, 1907, Compt. rend., Mém., vol. 2, p. 771, 1910.

[23] Boyle, R. W., Note on the solubility of radium emanation in liquids: Roy. Soc. Canada Trans., 3d ser., vol. 3, sec. 3, p. 75, 1909.

[24] McLennan, J. C., On the radioactivity of natural gas: Nature, vol 70, p. 151, 1904.

[25] Elster, J., and Geitel, H., op. cit. Wegener, Alfred, Untersuchungen über die Natur der obersten Atmosphärenschichten: Physikal. Zeitschr., vol. 12, pt. 1, pp. 170, 214, 1911. Schenk, Richard, Radioaktive Eigenschaften der Luft, des Bodens und des Wassers in und um Halle: Jahrb. Radioaktivität u. Electronik, Band 2, Heft 1, p. 19, 1905.

Radium emanation in the atmosphere.

Locality.	Radium (grams × 10^{-12} per cubic meter).	Observer.
Montreal	60	Eve.[a]
Cambridge	100	Satterly.[b]
Chicago	89	Ashman.[c]

[a] Eve, A. S., On the amount of radium emanation in the atmosphere near the earth's surface: Philos. Mag., 6th ser., vol. 16, p. 622, 1908.

[b] Satterly, John, The amount of radium emanation in the atmosphere: Philos. Mag., 6th ser., vol. 16, p. 584, 1908.

[c] Ashman, G. C., A quantitative determination of the radium emanation in the atmosphere: Am. Jour. Sci., 4th ser., vol. 26, p. 119, 1908.

The mean of these determinations is 83×10^{-12} grams of radium per cubic meter; and according to Rutherford,[26] if it is assumed that this quantity is constant up to a height of 10 kilometers, the quantity of radium necessary to keep up the supply is about 1 gram per square kilometer of the earth's surface. Sanderson[27] found that the air drawn from deep in the soil at New Haven contains emanation equivalent to 2.4×10^{-13} grams of radium and 1.35×10^{-6} grams of thorium per cubic centimeter.

A number of measurements of the radium content of sea water have been made, but the results are not satisfactorily concordant. Joly,[28] on the basis of 24 determinations, concluded that the average radium content is 0.017×10^{-12} grams per cubic centimeter, indicating a total oceanic content of 20,000 tons of radium, whereas Eve,[29] who examined six samples from the Atlantic, obtained an average value of only 0.0009×10^{-12} gram per gram. Joly,[30] in a more recent calculation, has adopted the intermediate figure 0.004×10^{-12} gram of radium per cubic centimeter of sea water, which he finds represents roughly the difference between the total quantity of adium brought into the ocean by the denudation of igneous rocks and the total quantities now found in sedimentary rocks and oceanic sediments.

ESTIMATES OF HELIUM PRODUCTION.

From the foregoing data on the distribution of the radio-elements in the earth's crust it is possible to obtain a general idea as to the quantity of helium produced in the normal course of radioactivity. Although the estimate is necessarily based on incomplete data, the value of the conclusions is enhanced by the fact that two entirely independent calculations led to fairly concordant results. The first calculation given below is based on the rate of loss of the earth's heat, and the second on the observed distribution of the radio-elements in the rocks.

If the rocks in the interior of the earth contain as much radium as the surface materials, the heat so generated would be many times as much as the earth gives off; hence it is necessary to assume also that most or all of the radium is concentrated in a comparatively thin surface layer, probably only 8 or 10 miles thick. Many authorities, however, believe that all the heat lost annually by the earth is compensated by radioactive processes, and this assumption furnishes a convenient basis for a calculation of the volume of helium so generated.

The simplest calculation may be based on the common though erroneous assumption that radium and its immediate products are the only elements concerned. If the average geothermal gradient is taken to be 1° F. in 64 feet, and the average conductivity of the rocks to be 0.0058, the amount of heat lost annually per square centimeter of the earth's surface is 41.4 calories.[31] As 1 gram of radium yields 134.4 calories an hour,[32] or 1,177,344 calories a year, it is evident that there must be 3.5×10^{-6} gram of radium beneath each square centimeter to maintain this loss of heat. One gram of radium emits 158 cubic millimeters of helium a year; and there are 51×10^{17} square centimeters in the earth's surface. Then $(3.5 \times 10^{-6}) \times 158 \times (51 \times 10^{17}) = 28{,}203 \times 10^{12}$ cubic millimeters of helium. That is, 28.2 million cubic meters of helium is produced annually by the decay of radium on the assumption that the loss of heat from the earth is compensated by that generated by radium.

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[26] Rutherford, E., op. cit., p. 634.

[27] Sanderson, J. C., The probable influence of the soil on local atmospheric radioactivity: Am. Jour. Sci., 4th ser., vol. 32, p. 169, 1911.

[28] Joly, J., Radioactivity and geology, p. 46, London, 1909; On the radium content of sea water: Philos. Mag., 6th ser., vol. 18, p. 396, 1909.

[29] Eve, A. S., On the amount of radium present in sea water: Philos. Mag., 6th ser., vol. 18, p. 102, 1909.

[30] Joly, J., Radioactivity of terrestrial surface materials: Philos. Mag., 6th ser., vol. 24, p. 704, 1912.

[31] This figure was adopted in 1882 by the committee on underground temperatures of the British Association for the Advancement of Science and according to C. E. Van Orstrand, who has made a careful study of geothermal gradients, the data that have since been gathered indicate that it is sufficiently near correct for the purposes of this calculation.

[32] Rutherford, E., Radioactive substances and their radiations, p. 581, Cambridge, 1913.

As some heat is generated by other members of the uranium series, however, and as thorium is even more widely distributed than uranium, it is obvious that a more nearly correct result may be obtained if all the radio-elements are taken into account. As shown on page 57, the average ratio of thorium to uranium in igneous rocks is about 2 to 1; in other words, each average gram of radioactive material consists of two-thirds of a gram of thorium, in equilibrium with its products, and one-third gram of uranium, also in equilibrium. Thorium in equilibrium generates 2.7×10^{-5} calories an hour, and uranium 7.7×10^{-5} calories an hour;[33] hence the average gram of radioactive material generates 4.4×10^{-5} calories an hour, or 0.385 calories a year. If we take the loss of heat from the earth at 41.4 calories per square centimeter, it is evident that there must be 107.5 grams of the thorium-uranium mixture beneath each square centimeter, or 35.8 grams of uranium and 71.6 grams of thorium. From the data given by Rutherford[33a] it follows that the helium generated by these quantities of uranium and thorium is 616×10^{-5} cubic millimeters a year, which, multiplied by the number of square centimeters in the earth's surface (51×10^{17}), gives 31.4 million cubic meters of helium per year.

The second method of calculation is based on the observed quantity of the radio-elements in surface rocks and on the assumption that these elements occur only in an outer layer of the earth's crust 10 miles thick. In such a calculation the metamorphic and sedimentary rocks and the oceanic sediments in sea water may be neglected, the average value for the igneous rocks alone being used. From the tables on pages 56 and 57 the average value of uranium per gram of igneous rock is seen to be 0.7×10^{-5} gram and that of thorium 1.5×10^{-5} grams. One gram of uranium in equilibrium emits 11×10^{-5} cubic millimeters of helium a year, and 1 gram of thorium 3.1×10^{-10} cubic millimeters; hence the total helium generated per year per gram of rock is 12.4×10^{-5} cubic millimeters. Assuming the average density of the outer layer of the earth's crust to be 2.5, we may compute that the weight of this layer is $10{,}421{,}615 \times 10^{9}$ grams per cubic mile, from which it follows that 12,923 cubic centimeters or 0.456 cubic foot of helium is generated per year per cubic mile. The surface of the earth is 1.97×10^{8} square miles, and a layer 10 miles deep contains about 19.7×10^{8} cubic miles. The total helium generated annually in this layer is thus 8.98×10^{8} cubic feet, or 25.4 million cubic meters.

If it is desired to estimate the helium produced in a restricted field, where the sedimentary rocks form a layer about 1 mile thick, the average uranium value for a block 10 miles deep may be reduced to 0.67×10^{-5} gram and the thorium value to 1.4×10^{-5} grams. On the other hand, the density of the rocks may be taken at 2.7, and the resulting figure is 0.465 cubic foot of helium per year per cubic mile, which is only very slightly larger than the average figure derived above.

The foregoing estimates are all based partly on assumptions and of course may be considerably in error. Becker,[34] for example, maintains that only about 25 per cent of the heat lost by the earth is generated by radioactivity, and if his view is correct the first two estimates would be reduced to 7 or 8 million cubic meters. Nevertheless, it seems safe to conclude that somewhere between 8 and 30 million cubic meters (282 to 1,060 million cubic feet) of helium is generated annually by radioactive processes. The bearing of this fact on the origin of the helium in natural gas is discussed on page 62.

THEORIES OF THE ORIGIN OF HELIUM IN NATURAL GAS.

REVIEW OF DATA.

In the foregoing pages the writer has endeavored to describe the geologic conditions under which helium-bearing natural gas occurs, and to review rather fully the occurrence of helium in other materials, in order to permit the reader to form his own judgment as to the most plausible hypothesis of the source and origin of the helium. At present this is all that can be done, for although the data are abundant in some respects, they are deficient in others and the evidence is not wholly concordant. It is apparent that considerable geochemical work will be necessary before any one hypothesis can be accepted; and it is the writer's purpose, in discussing the several hypotheses in the following pages, to point out some of the ways in which the problem can best be attacked.

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[33] Rutherford, E., op. cit., p. 583.

[33a] Idem, p. 560.

[34] Becker, G. F., Isostasy and radioactivity: Geol. Soc. America Bull., vol. 26, p. 201, 1915.

Before proceeding to the discussion of hypotheses it will be convenient to present, by way of recapitulation, the data already given.

REVIEW OF THE OCCURRENCES OF HELIUM.

I. Observed Occurrences.

A. IN NATURAL GAS.

(*a*) *United States.*—Helium constitutes from 0.5 to 2 per cent of certain nitrogen-rich natural gases in Kansas, Oklahoma, and Texas and occurs in smaller proportions in the gases of many other districts. The gases richest in helium are confined to strata of upper and middle Pennsylvanian age and occur close to the surface, the helium content usually decreasing with increasing depth. Gases containing from 0.25 to 0.5 per cent of helium occur in the lower Pennsylvanian of the Mid-Continent area, in the Mississippian and Silurian of Ohio, and in the Cretaceous of Montana, although in general the pre-Pennsylvanian gases are poor in helium, and the Cretaceous and Tertiary gases carry only traces or none at all. The helium-rich areas are not marked by igneous activity or by unusual structural conditions. There is no evidence as to whether or not the rocks in these districts are abnormally radioactive.

(*b*) *Europe.*—Helium has been detected in European natural gas in proportions as great as 0.38 per cent. The richest gas was found in a deep test hole in Alsace, probably in lower Mesozoic strata; the Tertiary gas in this locality is very poor in helium, and the Tertiary gases of Germany, Austria, Italy, and Transylvania are also poor. The helium content of these gases appears to vary roughly as their radioactivity.

B. IN MINERALS AND ROCKS.

A great variety of minerals have been found to contain at least traces of helium, and apparently only a few species are helium-free. Minerals rich in the radio-elements may contain several times their own volume of helium; ordinary rock-forming minerals are usually poor. In general the amount of helium in a mineral is proportional to its radioactivity and increases with age, indicating that the helium has been generated by the decay of the radio-elements; but certain beryls contain far more helium than can be explained in this way.

C. IN MINE GASES.

The gases of French and Belgian coal mines carry helium, and though the proportion is small the total volume emitted yearly is large. The coals themselves are very poor in the radio-elements, and helium is evidently not being generated in the coal nearly as fast as it is being emitted. There is, therefore, no evidence to connect the helium in the mine gases with radioactivity.

D. IN MINERAL-SPRING GASES.

The gases of many European mineral springs contain helium in proportions as great as 10 per cent. The volumes of helium emitted yearly by some of the springs represent all the helium that would be generated yearly by many tons of radium; hence this helium, like that in mine gases, probably represents the overflow or leakage of a great underground accumulation. Furthermore, the proportion of helium in the gases bears no relation to their radioactivity.

E. IN VOLCANIC GASES.

Small proportions of helium occur in the gases of certain Italian fumaroles, where there is no evidence to connect it directly with radioactivity.

F. IN THE ATMOSPHERE.

Helium constitutes 0.0004 per cent of the atmosphere near the earth's surface. In the upper atmosphere its proportion is greater.

G. IN CELESTIAL BODIES.

Helium is a prominent constituent of the solar chromosphere and of many nebulae and stars, though the radio-elements have not been identified with certainty in any celestial bodies.

II. Inferred Occurrences.

As the radio-elements generate helium in the course of their spontaneous disintegration, each occurrence of radioactive material connotes the presence of helium; but the radio-elements, because of their activity, can be detected in far smaller quantities than can the helium to which they give rise. The radio-elements are very widely disseminated through terrestrial materials, being present in minute proportions in practically all minerals and rocks, in the atmosphere, and in river and ocean water. Most petroleum and natural gas apparently contains some radium emanation. The helium generated by the radio-elements disseminated through ordinary rocks amounts to almost half a cubic foot per year per cubic mile of rock.

From the foregoing evidence certain broad conclusions may be drawn as follows:

1. The helium in most minerals is probably of radioactive origin; and as the radio-elements are disseminated through ordinary rocks in proportions sufficient to generate large volumes of helium in the course of a few million years, much of the helium in rocks has probably also originated through radioactivity.

2. As helium is very prominent in celestial bodies, whereas the radio-elements are not, it is probable that helium can and does occur in the universe entirely apart from the radio-elements, and that these elements may be regarded as compounds of helium and lead which form only under certain conditions. Accordingly, much of the helium in the earth may never have been associated with the radio-elements and may be primordial helium.

As the volumes of helium in some mineral-spring and mine gases are so large that incredible quantities of the radio-elements would be necessary to generate the helium as fast as it is emitted, it is probable that there are great stores of helium underground, the leakage or overflow of which appears in the spring and mine gases. These stores of "fossil" helium may be accumulations of the small volumes liberated by the disintegration of radio-elements through geologic time or they may in large part be primordial. The helium in natural gas may therefore be primordial or it may have been liberated through the decay of the radio-elements. As a great volume of helium is contained in the atmosphere there is the third possibility—which is not concerned with the ultimate origin of the element—that the helium in natural gas has in some way been derived from the atmosphere.

DERIVATION THROUGH RADIOACTIVITY.

FOSSIL HELIUM.

Since it was discovered that the alpha rays given off by the radio-elements are helium atoms it has been tacitly assumed by most scientists that all helium is the product of radioactivity. Even Moureu, who has plainly shown that the helium emitted by certain mineral springs can not be the product of contemporaneous radioactivity and who therefore regards it as "fossil" helium, apparently believes that this fossil helium is simply the accumulation of the small volumes of the gas liberated by the radio-elements during geologic time. It was natural, therefore, that Cady and McFarland, when they announced their discovery of helium in natural gas, should suggest that it originated in the decay of the minute quantities of radium disseminated through the rocks.

It is obvious that the helium in natural gas presents a problem different from that of the helium given off by mineral springs, for the emission of gas by the springs is a natural phenomenon which has been proceeding at least for many centuries, whereas the release of helium from the natural gas reservoir is artificial, its rate depending on the number of gas wells drilled. It would therefore be absurd to suppose that the supplies of helium in natural gas are being replenished underground as fast as they are brought to the surface, and it must be recognized at the outset that the helium in natural gas represents the accumulation of ages and is, to use Moureu's term, fossil helium.

DERIVATION FROM NORMALLY DISSEMINATED RADIO-ELEMENTS.

In order to test the theory briefly suggested by Cady and McFarland, that the helium has been derived from the disintegration of the radio-elements disseminated in normal quantities through the rocks, an examination of conditions in the Petrolia field, in Texas, will be convenient. According to independent estimates by E. W. Shaw and the writer (see p. 88), the Petrolia field originally contained about 120 billion cubic feet of natural gas, and as the percentage of helium in the gas is 0.93, the total helium must have been a little over 1 billion cubic feet. The producing area at Petrolia is about 10 square miles, but the gas probably represents the accumulation from an area of about 25 square miles. Let us assume for the moment that the helium in the gas represents all the helium generated in this area to a depth of 4 miles beneath the gas sands—in other words, in a block of 100 cubic miles of rock. It has been shown (p. 60) that the radio-elements disseminated through a cubic mile of the normal or average rock yield, by their disintegration, about 0.456 cubic foot of helium a year. The annual production of helium in 100 cubic miles is thus about 46 cubic feet, and the production in 25 million years would about equal the volume now found in the Petrolia field.

Two objections to the validity of this calculation at once present themselves. In the first place the basic assumption made by Strutt and others who attempt to calculate the age of minerals from the helium ratio is that most of the helium generated in a mineral remains in that particular grain or crystal during geologic time. The writer does not wholly agree with this view, for the mere existence of enormous accumulations of helium in natural gas in regions removed from unusual structural disturbances is sufficient to show that helium does migrate (unless, indeed, it is assumed that the helium has actually formed in the gas sands themselves); yet, on the other hand, if helium were free to leave the mineral as fast as it is formed and migrate upward, it is evident that the rocks near the surface everywhere would be saturated with helium. It is probable, therefore, that helium ordinarily does not migrate very far from the point of its origin and that little of the helium generated in the dense rocks several miles deep can have found its way into the gas sands. This difficulty might be lessened somewhat by assuming a shallower block of strata and a longer lapse of time, but it would still constitute a grave objection.

The other argument against this calculation is the self-evident one that normal conditions should bring about normal results—in other words, if the helium at Petrolia is supposed to have been generated by the radio-elements normally distributed through the rocks, why should not the same volumes of helium accumulate everywhere? Most natural gas contains at least a trace of helium, some of which has very probably been generated in the normal course of radioactivity; but the high percentage in the Petrolia gas, as well as in that of the Kansas fields, plainly indicates special conditions of some kind. So far as known, the conditions of accumulation in the helium-rich gas fields are no more favorable than in fields that produce gas free from helium, nor are there any known fissures or channels along which the helium could have risen from great depths. If helium is to be ascribed to radioactivity, therefore, it is necessary to postulate a local deposit of the radio-elements in each helium-rich district.

DERIVATION FROM LOCAL DEPOSITS OF THE RADIO-ELEMENTS.

As 1 ton of uranium in equilibrium yields about 1 cubic foot of helium a year, 40 million tons of uranium (or about 120 million tons of the Joachimsthal pitchblende) would yield in 25 million years the total estimated volume of helium at Petrolia. It is evident, however, that some of the helium would remain in the mineral grains in which it is formed, and that more would undoubtedly remain entangled in the rock close to the point of its origin; hence it is necessary to assume a deposit capable of generating considerably more helium than the gas sands themselves actually contain. On the other hand, it does not appear necessary to adopt the extreme view held by Strutt, that practically all the helium remains in the particles in which it was formed—in fact, if this view is adopted, it must be assumed that the helium has been generated in the gas sands. If it is supposed that only a half or a third of the helium generated has found its way into the gas sands, the size of the deposit that would have to be assumed at Petrolia is not incredibly large, and in all the other helium-bearing fields it would be smaller.

There appear to be no great geologic difficulties in the way of assuming such deposits, aside, of course, from the fact that there is no direct evidence of their presence. In the Kansas area it may be supposed that a uranium or thorium deposit existed in the old land mass from which the middle Pennsylvanian sediments were derived and that the débris from this deposit was laid down within a fairly small area. Monazite, for example, which is rich in thorium, is not uncommon as a minor constituent of clastic rocks and is locally abundant enough to form deposits of monazite sand. Or it might be supposed that uranium has since been introduced into the rocks by ascending solutions and precipitated as the secondary minerals carnotite or autunite. The carnotite ores of Colorado occur in sedimentary rocks rich in organic matter, which has evidently been a factor in their formation, and similar occurrences in the helium-bearing areas would not be surprising. It is not necessary to assume that these deposits are concentrated in a small area; it would be more reasonable, in view of the extent of the helium-bearing area in Kansas to suppose that the uranium minerals are widely disseminated through the rocks, and are perhaps only 50 or 100 times as abundant as in the normal or average rock of the earth's crust.

On the other hand, it might be supposed that the igneous rocks which doubtless underlie the Kansas area at a depth of less than 2 miles contain deposits of pitchblende, and that the helium liberated by these deposits has risen and mingled with the hydrocarbon gas formed in the sediments above. The presence of the buried granite ridge in the western part of the Kansas area might be regarded as supporting this view, for uranium minerals are more abundant in granite than in other igneous rocks. However, in addition to the fact that this granite lies not within but chiefly to the northwest of the helium-rich area, the practical absence of helium in all the deeper gases suggests that it originated not far beneath the base of the Kansas City group, the lowest horizon at which it is found in notable quantity. The fact that the helium occurs through a stratigraphic range of about 2,000 feet above this horizon might be taken to indicate that the active deposits are also scattered through this zone, or it might simply be supposed that the helium originated in the Kansas City group and has in part risen to upper beds.

In the Ohio area the helium is found at two widely separated horizons, the Berea and the Clinton sand, and the helium content of the gases below the Clinton sand is not known; hence in this district there is no evidence against the assumption that the helium has risen from considerable depths. At Petrolia the helium is known only at one horizon in the upper Pennsylvanian, and the deeper gases have not been tested, though gases from middle and lower Pennsylvanian strata in the Ranger district, 100 miles to the south, are poor in helium.

From a geologist's point of view, therefore, it would appear most reasonable to assume in the Kansas area an extensive disseminated or very lean deposit of uranium or thorium ore in the middle Pennsylvanian strata; at Petrolia a somewhat richer deposit at the same or a slightly higher horizon; and in Ohio a deposit in the Silurian to supply the Clinton sand, and perhaps another in the Devonian or Mississippian to supply the Berea.

These hypothetical deposits would then explain the occurrence of helium in certain fields and its absence in others, and also the fact that, in the Kansas area at least, the helium is confined to a certain group of formations and is absent in the gases both above and below that group.

There are certain other fragments of indirect evidence which offer some support to the general theory that helium is derived from the radio-elements. Because of the time element involved, the theory helps to explain the absence of helium in practically all the younger (Cretaceous and Tertiary) gases tested. Furthermore, the natural gas of Petrolia and Canada and the oil from many other localities are radioactive, apparently owing to the great solubility of radium and thorium emanation in petroleum. (See p. 58.) This suggests that petroleum may have some effect in concentrating the emanations by selective absorption, thus causing helium to be liberated in the oil itself. Except for Ramsay's statement that helium is insoluble in benzene there are no data as to the solubility of helium in oil; but it is probable that helium is at least only slightly soluble and that it would therefore be expelled from the oil and would mingle with the hydrocarbon gases almost as fast as it was formed. A third bit of evidence which may possibly bear on the subject is Van Orstrand's discovery[35] that the geothermal gradients in the Newkirk field, in northern Oklahoma, and in the Ranger district, in Texas, are very high, as would be expected if extensive deposits of the radio-elements were present. These districts do not produce gas very rich in helium, and there are no data as to the character of the gradient in the rich helium fields themselves, but an unusually high gradient even in the vicinity of those fields is of interest.

There are two other points which are more difficult to explain on this theory, or indeed on any other—the concentration of the helium at shallow depths, at least in the Kansas area, and the general association of the helium with nitrogen. The most reasonable explanation for the concentration of the helium near the surface in the Kansas area would be, according to this theory, the fact that the radioactive deposits also happen to lie near the surface. The only other explanation would appear to be that the helium, being very light, migrates upward through the rocks rather faster than the other gases. If so, it follows that the helium is constantly escaping from the shallow gas sands into the atmosphere, for if it is free to migrate through the denser rocks below it must certainly be capable of passing through the more pervious surface rocks. This explanation is not very satisfactory, for if helium has been constantly escaping a far greater volume than that still remaining in the sands must have been dissipated. Moreover, in the Ohio area there is no such concentration of helium near the surface, for the Clinton gas at a depth of about 2,300 feet carries as much helium as the Berea gas at about 500 feet.

The association of helium with nitrogen is difficult to account for. It has been suggested by Lind that the nitrogenous compounds present in organic shales may be destroyed by radioactivity and that the nitrogen so liberated would mingle with the helium generated in the same process. It is known, however, that water is decomposed by radioactivity, with the liberation of hydrogen, yet no hydrogen occurs in the helium-bearing gases, and if the radioactivity is not sufficient to decompose water in perceptible amounts, it is difficult to understand why the nitrogen compounds should be so extensively broken up. Similarly, helium occurs in mineral-spring gases, which are usually rich in nitrogen but in which no hydrogen is reported, so that little weight can be attached to this suggestion until definite evidence of the effects of radioactivity on nitrogenous compounds can be adduced. Another fact that militates against the view that the nitrogen in the gas is of organic origin is that Kansas and Ohio oils contain very small proportions of the nitrogen gases. California oil, on the other hand, is unusually rich in nitrogen, yet the California gas contains little nitrogen and no helium. (See pp. 37, 96.) However, the gas given off by uranium and thorium minerals is usually rich in nitrogen, which thus seems to have some general though unexplained relation with the radio-elements.

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[35] Van Orstrand, C. E., personal communication.

In order to raise the foregoing speculations to the rank of a definite hypothesis certain forms of evidence must be collected. Among the pertinent questions to be answered are the following:

1. Do the helium-bearing gas sands or the rocks adjoining them contain notable quantities of the radio-elements?
2. Is the geothermal gradient abnormally high in the helium areas, thus affording indirect evidence of the presence of radioactive deposits?
3. Are the oil-field waters or the waters of mineral springs in the helium areas strongly radioactive, and do they carry helium?
4. Is the petroleum radioactive, and if so is this due simply to dissolved emanations or does the ash of the petroleum carry uranium or thorium?
5. Is there any relation between the radioactivity of the gas and its helium content?
6. Does radioactivity rapidly destroy the nitrogenous compounds in oil shale, liberating free nitrogen?
7. Are the pores of the rocks beneath the helium-bearing gas sands largely filled with helium?
8. Is helium soluble in crude petroleum and is it more soluble in some varieties than in others?

DERIVATION FROM FAINTLY RADIOACTIVE ELEMENTS.

Discovery of the fact that potassium and rubidium are faintly radioactive has led several observers to suggest that other elements may also emit radiations. Potassium and rubidium themselves apparently emit only beta rays and therefore do not generate helium, but there is a possibility that other elements may emit alpha radiations of low velocity. As described on page 14, the radioactivity of a substance is ordinarily measured through its property of ionizing gases, this property being due in part to the very high speed at which the active particles are expelled. Rutherford states that if alpha particles (helium atoms) were expelled at a velocity of about half that at which they are given off by uranium they would not cause ionization and hence would not be detected by the ordinary methods of examination. In other words, there is a possibility that certain common rock-forming elements may emit alpha radiations at low velocity and may therefore generate helium.

In this connection it will be recalled that Strutt interpreted the occurrence of large volumes of helium in some potash minerals as evidence that potassium generates helium, though the fact that no alpha rays from potassium have ever been detected casts doubt on this view. Similarly the anomalous volumes of helium found in beryls were formerly thought to indicate that the element glucinum is radioactive, but this idea was disproved by Piutti, who found no helium in six specimens of phenacite, which is richer in glucinum than beryl itself.

Recently the hypothesis that helium in natural gas may result from the disintegration of elements not known to be radioactive has been suggested by R. B. Moore,[36] who is familiar with the conditions under which the helium occurs and whose extensive work in the field of radioactivity deserves special consideration. There is, of course, no direct evidence for this suggestion, but Dr. Moore proposes to investigate the matter experimentally, and his results will be awaited with interest. If it can be shown that common rock-forming elements generate helium, it would probably be easy to explain the source of the helium in natural gas, though it may be pointed out that the reverse difficulty might then arise—the problem of explaining the absence of helium in other areas.

Our knowledge of radioactivity is still fragmentary, and it will not be surprising if future discoveries compel us to modify our present ideas considerably. Clarke[37] suggested many years ago that the chemical elements have been developed by a process of evolution from simpler forms of matter, and the more recent discovery of changes in the opposite direction, such as the disintegration of uranium into simpler bodies, offers considerable support to this view. Dr. Moore, in discussing with the writer his theory that other elements may prove to be radioactive, sums up his attitude in the words "I can not help thinking that something is going on that science knows nothing of at the present time, and that the presence of helium [in natural gas] can not be accounted for by anything that comes within the scope of our present knowledge." The possibility that other elements also disintegrate can not be ignored, though the helium in natural gas should not be ascribed to such action unless positive evidence can be adduced or unless all other hypotheses are proved inadequate.

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[36] Personal communication.

[37] Clarke, F. W., Evolution and the spectroscope: Pop. Sci. Monthly, January, 1873.

PRIMORDIAL HELIUM.

In contrast with the views of those who ascribe all helium to radioactive processes is the theory developed by Becker, Clarke, and others that some and perhaps much of the helium in the globe is primordial and has had no connection with radioactivity. It is, of course, difficult to adduce positive or direct evidence in favor of such a theory, and it therefore rests on certain broad deductions, chief among which are the following:

1. The prominence of helium and the apparent absence of uranium and thorium in celestial bodies indicate that helium can and does occur in the universe apart from the radio-elements, which may therefore be regarded as combinations of helium and some other element, apparently lead.

2. The disintegration of uranium and thorium is attended by the emission of an enormous quantity of heat; hence their formation must be accompanied by the absorption of heat and could take place only under conditions of great temperature and pressure. Conditions favorable to their formation doubtless existed in the earlier stages of the cooling earth and may exist in the interior of the earth to-day.

3. If uranium and thorium are to be regarded simply as combinations of helium and lead, there is no reason to suppose that all the helium in the earth entered into this combination, for it is clear that all the lead did not.

These conclusions, though not susceptible of actual proof, are none the less forceful and deserving of consideration. The concept of primordial helium removes the quantitative difficulties which confront all hypotheses of derivation from the radio-elements. The existence of helium in mineral-spring and mine gases in volumes far larger than can be explained by the radioactivity of these gases indicates that there are large accumulations of helium underground, and these accumulations can be explained at least as well by the primordial theory as by any theory of radioactive origin. The same is true of the helium in volcanic gases. On the other hand, the helium in most minerals is obviously derived from the radio-elements, and most minerals evidently contain a large proportion of all the helium that has been generated within them; hence it may be argued that the great bulk of all helium produced by radioactivity is confined in the rocks close to the point of its origin and that it can not have entered into the great accumulations which find their escape in various natural gases. This is, in fact, the view held by Strutt and many others who, though apparently ascribing all helium to radioactivity, ignore the evidence of natural gases and contend that helium for the most part remains in the mineral grains in which it is formed.

Another difficulty confronting those who oppose the concept of primordial helium is that of explaining the great volume of helium in the atmosphere. C. E. Van Orstrand has calculated from the figures given by Jeans (p. 52) the total volume of helium in the atmosphere and finds it to be 58×10^{12} cubic meters. As shown on page 60, the total volume of helium generated annually in the earth by the disintegration of the radio-elements is probably somewhere between 8 million and 30 million cubic meters. At the maximum rate all the helium in the atmosphere would therefore be formed in 2 million years; the minimum rate would require 7¼ million years. It is generally admitted, however, that only a small proportion of the helium generated can have migrated through the rocks and escaped into the atmosphere, for very large volumes are known to be entangled in the rocks and to be trapped in accumulations of various natural gases. Even assuming that helium is produced at the rate of 30 million cubic meters a year, therefore, it seems probable that a longer time would be required for the accumulation and escape of all the helium in the atmosphere than most geologists are willing to allow for the age of the earth.

Broadly considered, the theory of primordial helium thus has many advantages, though its detailed application to the helium in natural gas is more difficult. In order to explain the occurrence of helium in some localities and not in others, it is necessary to postulate special structural conditions of some kind which would permit the helium to rise from below. The only known unusual structural feature in any of the helium areas is the buried granite ridge in the Mid-Continent region (see pp. 22, 35), but the fact that the deep gases nearest the granite are poor in helium indicates that little significance can be attached to this feature. All the other helium-bearing gas fields, except the Havre field, are located in regions of gentle structure which are remote from igneous activity; and on the other hand several fields examined which are close to areas of structural disturbance and igneous action produce gas that is practically free from helium. (See p. 35.) Furthermore, the stratigraphic distribution of the helium—including its absence not only in the Permian and Mississippian gas of the Mid-Continent area but also in practically all Cretaceous and Tertiary gases—is very difficult to explain.

On the other hand, the primordial theory is not incompatible with the common occurrence of helium near the surface and with its usual association with nitrogen. As already noted, if the concentration of helium near the surface is ascribed to its tendency to migrate upward it must be admitted that the helium is constantly escaping from the shallowest sands into the atmosphere; and according to this view the volumes of helium involved are so large that they can be explained only by the primordial theory or some other which postulates an almost illimitable supply.

The association of helium with nitrogen in natural gas, in mineral-spring gases, and in the gases given off by rocks would also be reasonable according to the primordial theory, especially as it is very difficult to see how the nitrogen in natural gas can have been derived from the petroleum or from other organic sources. Some observers have concluded that the common occurrence of nitrogen in deep earth gases is due to the decomposition of nitrides in the earth's interior; others, like Moureu, adopt an opposite view, pointing out that nitrogen is a chemically inactive gas and should therefore be found accompanying the truly inert gases, helium, argon, krypton, etc. Argon and neon in very small proportions have been detected in some of the helium-bearing gases of Kansas, but unfortunately no quantitative determinations have been published and definite evidence on this point must await further work.

ATMOSPHERIC HELIUM.

The great supply of helium in the atmosphere and the common occurrence of helium-rich gases in shallow strata naturally suggest that the helium in natural gas may be of atmospheric origin. Owing to the lack of evidence this view can at present be regarded only as conjectural. Two possibilities present themselves—that the helium, nitrogen, argon, etc., represent the inactive residue of air that has been entrapped in the sediments; or that these gases have been absorbed by the decaying organic matter from which the petroleum is derived and have been later concentrated in some manner.

When sediments are laid down offshore a certain amount of air is probably trapped in the interstices; and if these sediments should be raised above sea level during a period of aridity, when the ground-water level is low, and then resubmerged and covered by further deposits, a large quantity of air might be permanently trapped.[38] The oxygen and carbon dioxide in this air would be chemically fixed as oxide and carbonate, and some of the nitrogen might also enter into combination, leaving a residue of nitrogen, helium, argon, etc. This theory has the following definite objections: (1) The formation of nitrogenous compounds under ordinary temperature and pressure seems improbable. (2) Air contains about 2,300 times as much argon as helium, and although argon is strictly an inert gas, differing from helium chiefly in its greater solubility in water, the natural gases of Kansas apparently contain far less argon than helium. (3) The Permian sediments of Kansas and Oklahoma are supposed to be in part continental deposits laid down under arid conditions which were presumably very favorable to the entrapping of air, yet the Permian gases are very poor in helium.

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[38] This theory has been developed and discussed by Frank Reeves (The absence of water in certain sandstones of the Appalachian oil fields: Econ. Geology, vol. 12, p. 354, 1917).

analyses thus indicate that the gas is not especially rich in helium, despite its shallow depth and the location of the field in the same general belt as the helium-rich Augusta and Eldorado fields, to the south.

ELDORADO FIELD.

LOCATION.

The Eldorado field, which is in th part of Butler County, Kans., is o most productive oil fields in the Mid-

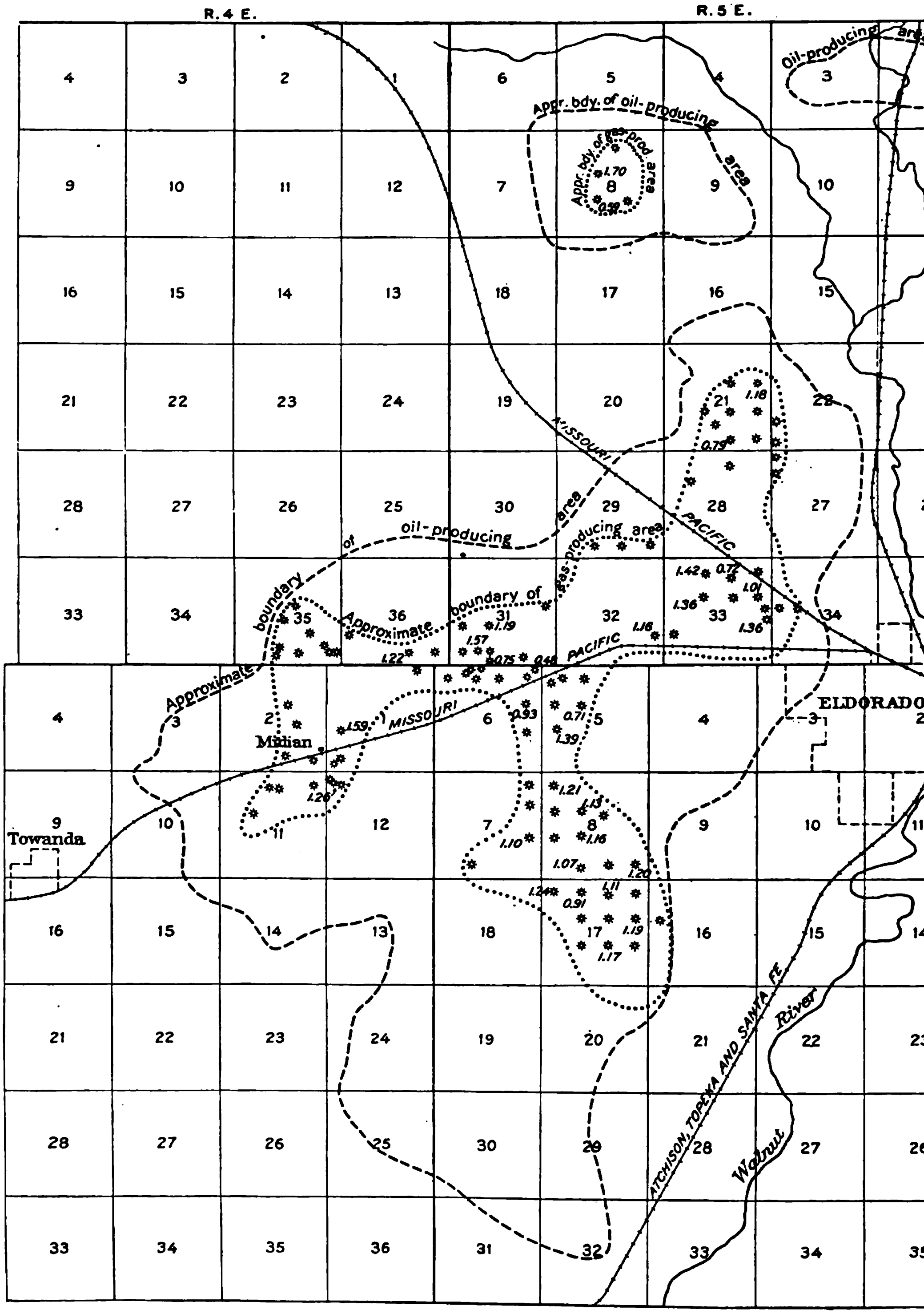

FIGURE 8.—Sketch map of Eldorado field, Kans., showing gas wells, location of samples, and helium content of gas

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Appalachian and northern interior oil and gas regions, which contribute about 70 per cent of all the gas produced annually in the United States. This neglect was due partly to lack of time and partly to the fact that the many analyses of gas from those regions that have been made and published during the last 50 years show uniformly low nitrogen content and therefore indicate that the gas is poor in helium. It is believed that if gas of low heating value—that is, rich in nitrogen and helium—were being produced in any of the eastern fields the fact would be known or would have been discovered incidentally during the investigation. The prospects of discovering further supplies of gas similar to that produced in Vinton County are therefore believed to be slight, though it must be recognized that this conclusion is based on inference rather than on detailed observation.

In the course of the investigation about 325 samples of gas, most of them collected by members of the Geological Survey, were tested for helium. The results of the tests and all particulars regarding the source of the samples and the supply of the gas available are presented in tabular form on pages 96–109. The tests made by Cady and McFarland in 1906 have also been included in the tables, which thus present a concise summary of our present knowledge regarding the distribution, occurrence, and available supply of helium-bearing natural gas in the United States.

The location of the fields from which the samples were taken is shown on Plates I and III and figure 5 (p. 29), and the general geology of the helium-bearing districts has been discussed. In the following pages brief descriptions of the more important helium-bearing gas fields will be given, with special reference to the location and economic relations of the fields, the volume of gas available, and the probable duration of the supply. No attempt will be made, however, to describe all the fields from which samples were collected, or even to give complete geologic descriptions of the fields which are at present the chief potential sources of supply. The statements as to developments of course refer to the time at which this paper is written.

MID-CONTINENT REGION.

ELMDALE FIELD.

The Elmdale gas field is in Chase County, Kans., about 5 miles west of Cottonwood Falls. The field as at present developed lies mostly south and east of Elmdale, or in the southeast corner of T. 19 S., R. 7 E., but there are also three isolated groups of successful wells some miles north and northeast of the field. Although the surface rocks in this general district are normally of Permian age, a large and prominent anticline or dome has brought the upper Pennsylvanian strata to the surface in the vicinity of Elmdale. The anticline, which represents a structural elevation of about 200 feet, has a north-south diameter of about 12 miles and an east-west diameter of about 9 miles; its center is in the valley of Cottonwood River, about 3 miles southwest of Elmdale. Despite the size and altitude of this fold it has not been productive of oil, and two deep wells near Elmdale encountered granite at a depth of about 1,900 feet.

Several dozen gas wells have been drilled on or close to the anticline. Gas is found at three horizons, in beds known as the 150-foot sand, the 350-foot sand, and the 580-foot sand. Wells have been drilled to the 150-foot sand at a number of farmhouses, where the gas is used directly for domestic purposes. The initial pressure is said to be about 17 pounds to the square inch and the flows small, but the wells are long-lived. The 350-foot and 580-foot sands have been developed on a commercial scale by the local gas company, which supplies about 300,000 cubic feet a day to Cottonwood Falls, Strong City, and neighboring towns. The flow of the wells is comparatively small, and the "settled" pressure is only 20 to 30 pounds. The sands appear to be productive nearly everywhere throughout a large area, however, and it is claimed by local engineers that it would be possible to develop a production of 8 to 10 million cubic feet a day, provided all three sands were tapped.

Samples of gas collected from the 350-foot and 580-foot sands showed, respectively, 0.35 and 0.50 per cent of helium, and a sample collected by Cady and McFarland from the 150-foot sand in 1906 showed 0.56 per cent. The analyses thus indicate that the gas is not especially rich in helium, despite its shallow depth and the location of the field in the same general belt as the helium-rich Augusta and Eldorado fields, to the south.

ELDORADO FIELD.

LOCATION.

The Eldorado field, which is in the central part of Butler County, Kans., is one of the most productive oil fields in the Mid-Continent

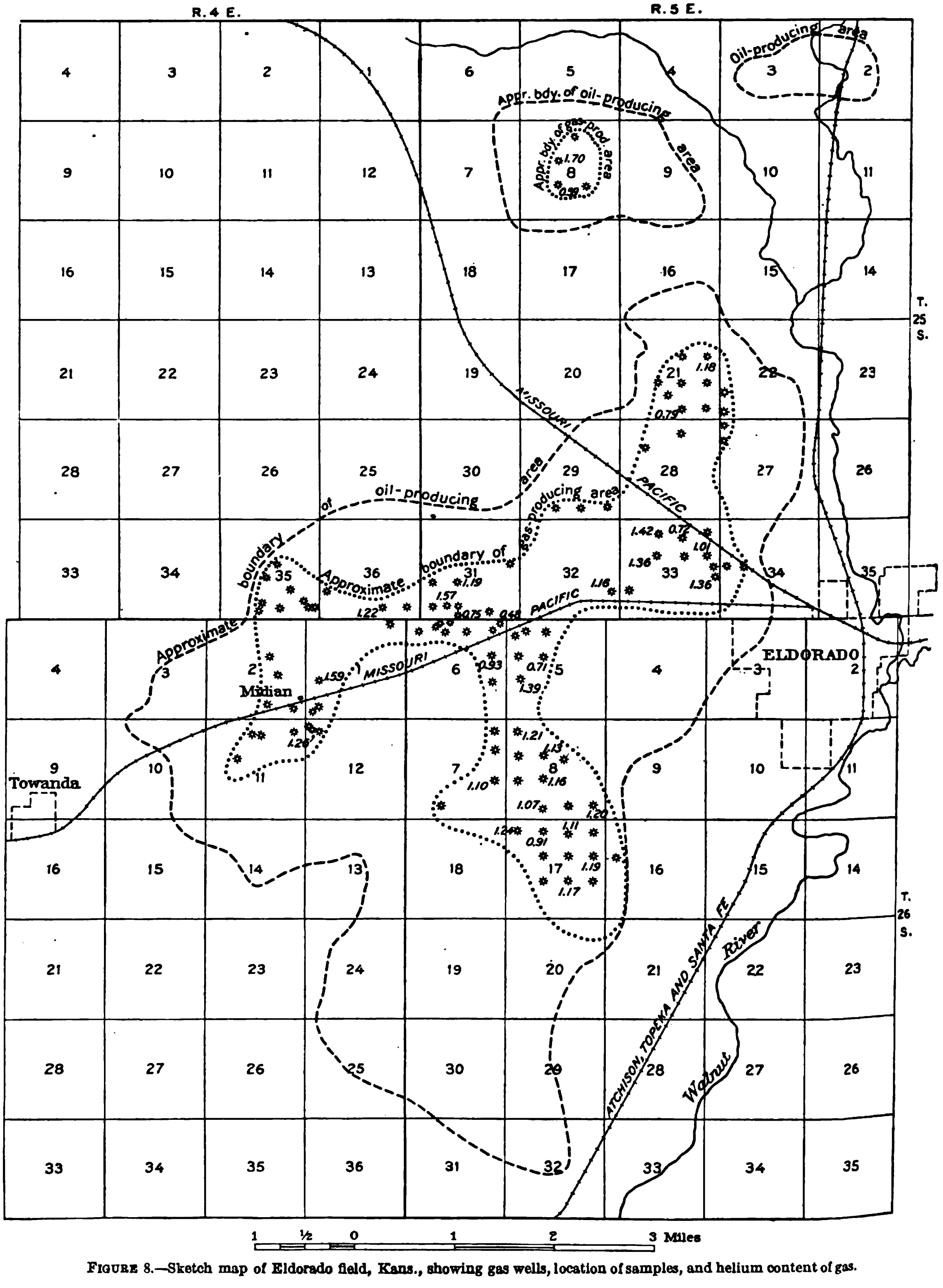

FIGURE 8.—Sketch map of Eldorado field, Kans., showing gas wells, location of samples, and helium content of gas.

region and is at present one of the chief potential sources of helium-bearing natural gas. The field lies chiefly in T. 25 S., R. 5 E., but extends some distance into T. 26 S., R. 5 E., and T. 24 S., R. 4 E. (See fig. 8.) The town of Eldorado, on the eastern edge of the field, is at the junction of the Missouri Pacific and Atchison, Topeka & Santa Fe railroads. The town has a population of about 15,000 and the nearest city, Wichita, about 30 miles to the west, has a population of about 60,000 and is an important railroad center.

GEOLOGIC OUTLINE.

The productive sands in the Eldorado field are of Pennsylvanian and Mississippian age, the highest occurring near the top of the Pennsylvanian and the lowest in Mississippian and probably in places in older rocks. The highest producing sand is encountered at a depth of 650 feet and according to Fath[41] occurs in the lower part of the Wabaunsee group. It is productive only in the northeastern part of the field, where it yields considerable oil but practically no gas. The field's output of gas is obtained from the next lower productive sands, which occur at average depths of 900, 1,200, and 1,475 feet. The sands at 900 and 1,200 feet are fairly persistent throughout the producing area, but they are zones or groups of sands which individually are lenticular and discontinuous. These zones, which yield the great bulk of all the gas produced in the field, occur in the Shawnee, Douglas, and Lansing groups. The main oil zone is encountered at an average depth of 2,500 feet and occurs in Mississippian rocks corresponding to the Boone limestone. In places it probably extends downward into older rocks. This zone yields the bulk of the oil produced in the field, and a great many oil wells have therefore penetrated the overlying gas sands. In most of these wells the gas has been mudded off, but the gas pressure in a sand penetrated by so many wells is naturally affected, despite precautionary measures.

The Eldorado field lies on a prominent anticline, on which there are many irregular cross folds and minor wrinkles. According to Fath, the distribution of both oil and gas is closely related to the structure; the gas sands are productive only in the highest parts of the fold, and the oil sands are productive over a much larger area which extends from the crest of the fold well down its flanks. (See fig. 8.) Owing to the lenticular character of the sands and to the variation in their porosity, however, neighboring gas wells may have very different capacities.

QUALITY OF THE GAS.

As shown by the tests of 33 samples (see p. 98), the gas of the Eldorado field ranges in helium content from 0.48 to 1.70 per cent. Only two samples, however, show less than 0.71 per cent, and the average of all the samples is 1.12 per cent. Nineteen samples of gas from the 900-foot zone show an average helium content of 1.20 per cent, and 13 samples from the 1,200-foot zone an average of 1.01 per cent.

The Eldorado gas varies considerably in composition, and there appear to be no marked and constant differences between the gases from different sands. The general quality of the gas is shown by the following representative analyses:

Analyses of gas of Eldorado field, Kans.

	900-foot zone.	1,200-foot zone.	1,400-foot zone.
Carbon dioxide (CO_2)	0.56	0.10	0.12
Oxygen (O_2)	.00	.14	.10
Methane (CH_4)	54.58	62.68	31.36
Ethane (C_2H_6)	3.33	11.82	12.78
Residue (N_2, etc.)	41.53	25.26	55.64
	100.00	100.00	100.00
Heating value (British thermal units)	584	811	524

VOLUME AND DURATION OF THE GAS SUPPLY.

Although the Eldorado field is still comparatively young, having been opened late in 1915, its gas resources have been heavily drawn upon in the last four years and are now probably about two-thirds exhausted. The maximum daily production of about 20 million cubic feet was reached at the end of 1916, when the combined open flow of all the wells was about 60 million cubic feet. In May, 1918, the daily production was about 10 million and the total open flow about 25 million cubic feet. The entire production of the field is used for drilling and pumping the oil wells, but it constitutes only about two-thirds of the volume required for this purpose.

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[41] Fath, A. E., report on the Eldorado oil and gas field, Kans. (in preparation).

The first wells in the field had an average rock pressure of 465 pounds to the square inch but in May, 1918, the average pressure of all the wells in the field had fallen to 140 pounds. This rapid decline in pressure, which is shown graphically in figure 9, is due chiefly to the fact that the wells have been allowed to produce from 30 to 50 per cent of their open flow, though a contributing factor has doubtless been the unavoidable waste of gas caused by the fact that the gas sands have been punctured by so many wells drilled for oil. It will be noted, however, that the greater part of the decline in pressure took place in 1916, the period during which most of the gas wells were drilled and when also the daily production was largest. From the middle of 1917 to the middle of 1918, when the drilling became less active and the daily production was reduced to 10 or 12 million cubic feet, the decline in pressure became very moderate.

As the rock pressure declines the open flow and therefore also the production diminishes; but as the production decreases the decline in pressure becomes less rapid. In the later stages of the life of a field the curve of pressure decline therefore becomes flatter, and a small production may be maintained for a comparatively long period. It is evident from figure 9 that the Eldorado field has entered this stage and that during the next two or three years the field may be relied on to furnish a moderate production, provided the wells are not made to yield too heavily.. If the daily production of the field had been reduced to 4 million cubic feet in the middle of 1918, this production could probably have been maintained for at least three years. On the assumption that the average helium content of the gas is 1.12 per cent, this would represent a daily production of 44,800 cubic feet of helium.

It will be noted that the curve in figure 9 shows a slight upward trend in the first part of 1918. This is due to the bringing in of several large gas wells on a small dome then recently discovered at the north end of the field. Although the gas-bearing territory in the main field has now been practically all drilled, there is a possibility that other small additional supplies will be discovered, and that the life of the field will be correspondingly increased.

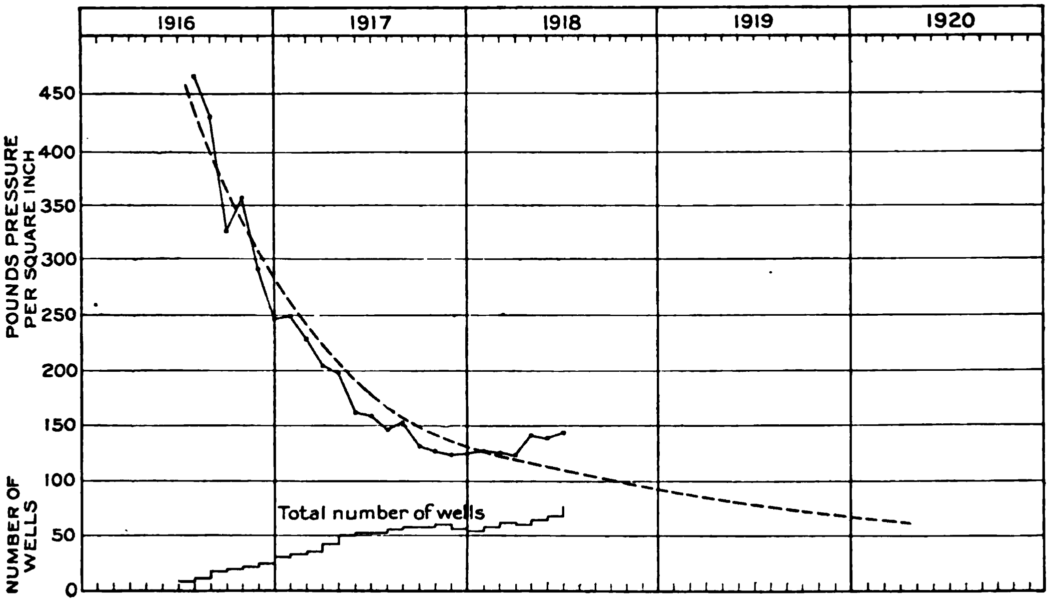

FIGURE 9.—Curve showing decline of average rock pressure of a typical group of wells in the Eldorado field, Kans.

AUGUSTA FIELD.

LOCATION.

The Augusta field is in the southwestern part of Butler County, Kans., its north end being only about 5 miles south of the southern limit of the Eldorado field. The Augusta field lies chiefly in Tps. 27 and 28 S., R. 4 E. The town of Augusta, which has a population of about 1,500, is in the east-central part of the field. It is situated on the St. Louis-San Francisco and Atchison, Topeka & Santa Fe railroads. (See fig. 10.)

GEOLOGIC OUTLINE.

The general geology of the Augusta field is similar to that at Eldorado, and the producing zones are roughly equivalent to those already described for that field. The 650-foot zone, however, which yields only oil in the Eldorado field, carries at Augusta a "wind gas" very rich in helium. The main gas sands form a zone ranging in depth between 1,400 and 1,600 feet. Individual sands can not be traced for great distances, and the gas seems to occur irregularly through this zone, rather than at several distinct horizons, as at Eldorado. The principal oil sands lie at depths of about 2,000 to 2,400 feet.

The Augusta field is on a large anticlinal fold which represents a southwestern continuation of the Eldorado anticline. The Augusta fold, like that at Eldorado, is irregular, and it consists of at least two fairly distinct anticlines. The larger one, which is known as the main Augusta anticline, lies chiefly in T. 28 S., R. 4 E. It yields a large proportion of the oil produced in this field and at present practically all the gas. The smaller fold, which is known as the North Augusta anticline, is in the central part of T. 27 S., R. 4 E., and is separated from the main anticline by a structurally low and barren area.

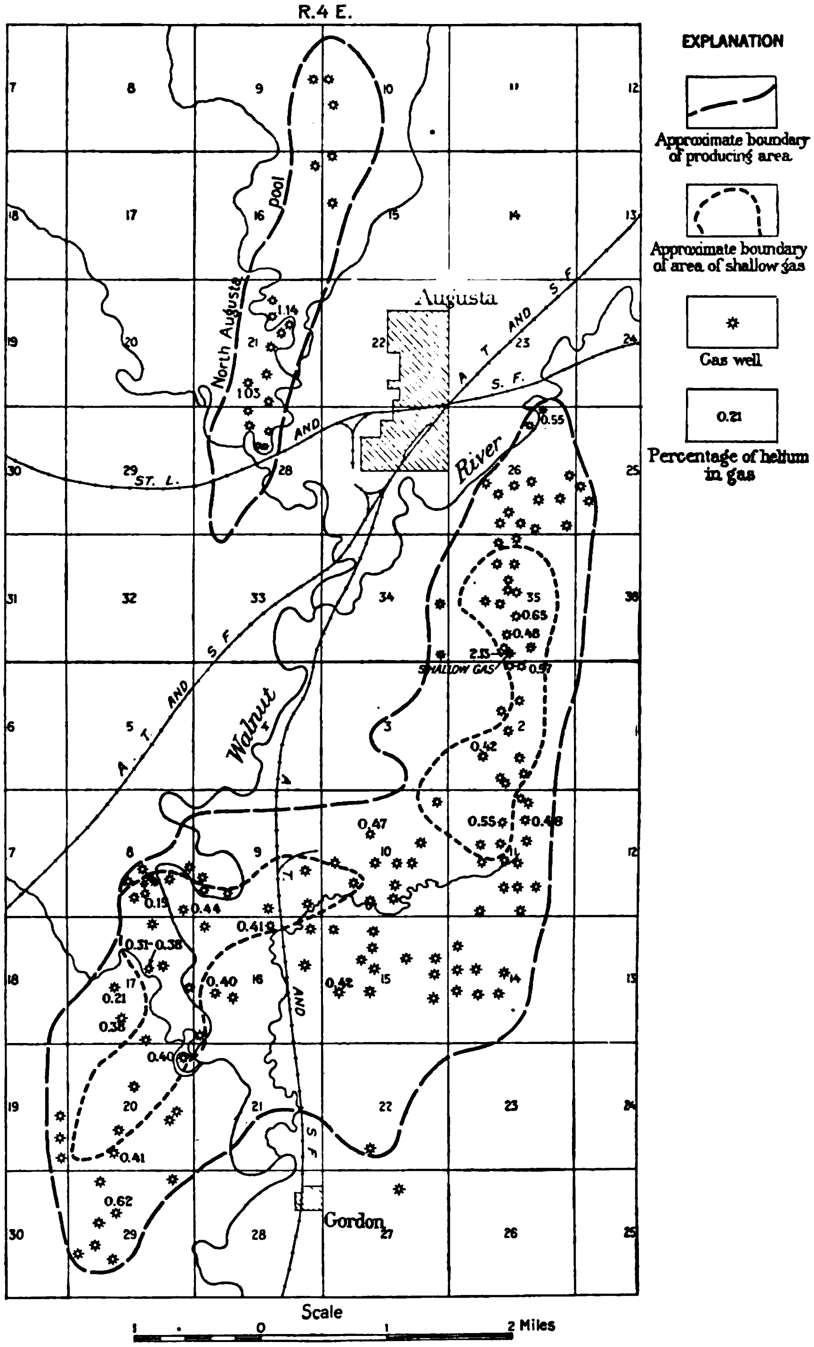

FIGURE 10.—Sketch map of Augusta field, Kans., showing gas wells, location of samples, helium content of gas, and areas in which the shallow gas rich in helium occurs.

QUALITY OF THE GAS.

Twenty-six samples of Augusta gas have been tested for helium, with the results shown on page 98. Two samples of gas from the shallow zone (450 to 650 feet) contained 1.94 and 2.13 per cent of helium. Two samples of the gas occurring at depths of 1,200 to 1,400 feet on the North Augusta anticline, in T. 27 S., R. 4 E., showed 1.03 and 1.14 per cent of helium. The remaining samples represent the gas that occurs at depths of 1,200 to 1,500 feet on the main anticline and now constitutes the great bulk of the output. This gas ranges in helium content between 0.16 and 0.65 per cent, though only three samples showed less than 0.38 per cent, and the average of the 22 samples is 0.43 per cent.

There are therefore in the Augusta field three distinct types of gas containing 2.04, 1.09, and 0.43 per cent of helium. The richest and the poorest of these gases occur at different depths on the main anticline, which comprises the central and southern parts of the field. The intermediate gas occurs at about the same depth and horizon as the poorest gas but on the North Augusta anticline. It is interesting to note that the gas produced on this anticline thus differs greatly in helium content from that produced in the main field and resembles the Eldorado gas; and it is said, furthermore, that the North Augusta oil resembles the Eldorado oil in gravity and composition more closely than the oil of the main Augusta field.

The shallow gas carrying about 2 per cent of helium is very high in nitrogen, as shown by analysis 17, page 39. The gas produced in the North Augusta field is on the average only slightly higher in nitrogen than that of the main field, though containing about twice as much helium. This is shown by the following analyses, kindly furnished by Prof. H. C. Allen:

Analyses of gas from the Augusta and North Augusta fields, Kans.

	Augusta.		North Augusta.	
Carbon dioxide (CO_2)	0.21	0.32	0.00	0.07
Oxygen (O_2)	.00	.12	.31	.19
Methane (CH_4)	76.48	63.32	50.22	63.92
Ethane (C_2H_6)	12.60	13.45	21.32	5.67
Higher hydrocarbons	.44	.13	.00	.19
Residue (N_2, etc.)	10.26	22.63	28.15	29.96
	99.99	99.97	100.00	100.00
Heating value (British thermal units)	961	844	853	719

QUANTITY OF SHALLOW GAS AVAILABLE.

As shown in figure 10 the shallow gas containing about 2 per cent of helium occurs only in certain parts of the field, being apparently confined to two areas, aggregating about 2,000 acres, on the main Augusta anticline. These areas occupy the two highest points on the anticline, and their shape and extent are determined almost entirely by structural conditions. Within these areas, however, the distribution of the gas is irregular and is evidently controlled by variations in the porosity of the sand, for out of about 200 deep oil and gas wells drilled in the shallow-gas territory only about 75 encountered volumes of this gas large enough to be noted and reported by the drillers. The volumes reported range between a few thousand and 3½ million cubic feet daily, with an average of perhaps 400,000 cubic feet. The rock pressure of this gas has never been gaged, though an inconclusive test made by the writer suggests that it is probably between 50 and 75 pounds to the square inch.

As the shallow gas consists so largely of nitrogen that it is practically incombustible, no attempts have been made to produce it, but owing to the drilling of so many deeper wells through its horizon a considerable volume of the gas has doubtless escaped. The Empire Gas & Fuel Co., in a noteworthy spirit of conservation, has taken pains to mud off or seal this horizon in all its wells, but most of the other operating companies have taken no precautions to prevent the gas from escaping. On the other hand, the variable porosity of the sand itself has evidently prevented very extensive loss of the gas, for the volumes reported in wells drilled recently average about as large as those in the early wells. Owing to the irregular distribution of the gas, to the lack of information as to the rock pressure, and to the fact that an indeterminate quantity has escaped it is impossible to estimate the total volume still in the sands, but it is probably little more than half a billion cubic feet.

QUANTITY OF DEEP GAS AVAILABLE.

The Augusta field, which was opened late in 1913, produced up to the middle of 1918 between 30 and 35 billion cubic feet of gas, all of which was derived from the group of sands occurring at depths between 1,400 and 1,600 feet. The original rock pressure was slightly over 400 pounds to the square inch, but in July, 1918, the average pressure was about 140 pounds. At that time the daily production of the field was almost 7 million cubic feet, and the total open flow was about 20 million cubic feet.

The gas resources of the North Augusta anticline are now almost exhausted, and the present output of the field is derived almost wholly from the main anticline. The field is now well outlined, and there is little prospect of the discovery of new supplies, although a few additional wells can yet be drilled. A study of the curve of rock-pressure decline indicates that unless water troubles become too serious the field should be capable of producing an average of 3 to 4 million cubic feet a day until some time in 1921.

The comparatively low helium content of this deeper gas renders it unfavorable as a source of helium, but if it were mixed with the shallow gas in proportions of 3 to 1 the average helium content of the mixture would be about 0.8 per cent.

DEXTER-OTTO DISTRICT.

LOCATION.

The Dexter-Otto area comprises that part of eastern Cowley County, Kans., shown in figure 11. A very prominent anticline traverses this area and extends both north and south beyond the territory shown on the map. Two deep oil wells, many shallow gas wells, and a number of dry holes have been drilled on or near the axis of the fold. There are three areas in which gas is produced—the vicinity of Dexter, an area 2 miles north of Otto, and an area 5 miles southeast of Otto. In all these areas the gas is rich in helium, carrying from 0.5 to 1.9 per cent, but the present supply is small, and the chances of a great extension are rather slender.

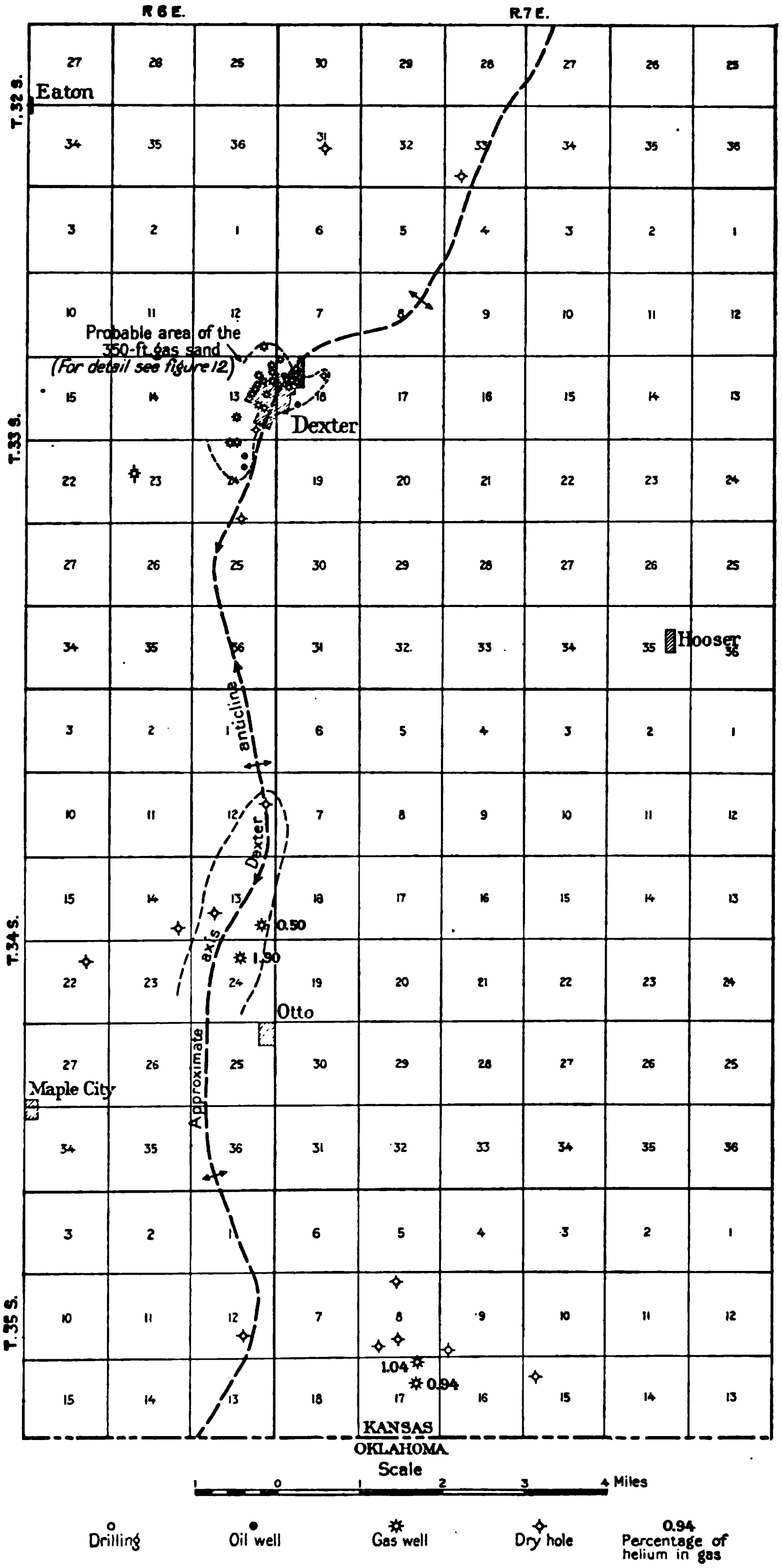

FIGURE 11.—Sketch map of Dexter-Otto area, Cowley County, Kans., showing location of wells sampled and helium content of gas.

OLD DEXTER FIELD.

Gas was discovered at Dexter in 1905 at a depth of 325 feet, and during 1906 to 1908 22 producing wells and 1 dry hole were drilled. Most of the wells were put down within the town limits, and the field, though very productive, was small. The gas sand ranges between 20 and 55 feet in thickness and is encountered at depths between 300 and 350 feet. The initial rock pressure was unusually high for this depth, being 110 pounds to the square inch, and the maximum open flow was 10 million cubic feet a day, though the average was about 3 million cubic feet. Several deep wells drilled for oil in this area in the last two years have found some gas at the same horizon, one well having found, it is said, enough gas to blow the water out of a 16-inch hole. At present half a dozen of the old wells are still producing a few thousand cubic feet a day (See fig. 12.)

The Dexter gas is famous because of its peculiar composition and especially because when examined by Cady and McFarland in 1905 it was the only gas of this type known, its analysis having led to all the subsequent work on helium. Two samples tested by Cady and McFarland in 1905–6 showed 1.64 and 1.84 per cent of helium; two others collected by the writer in August, 1918, showed 1.68 and 1.83 per cent; and one collected by a local operator in the spring of 1918 showed only 0.95 per cent, but this sample possibly contained air.

The Dexter field is regarded as exhausted, and there appears to be no warrant for expecting the discovery of further large supplies. As the largest wells were drilled on the western edge of the pool, however, it is believed that some gas at least can be obtained by drilling in the central or western part of sec. 13. (See fig. 12.) The small cost of the wells and the very high helium content of the gas would compensate in a measure for the small volumes that can probably be obtained.

The only other noteworthy occurrence of gas in the vicinity of Dexter was reported from the Monitor Oil Co.'s well in the NE. ¼ sec. 24. In this well a large volume of gas, variously estimated at 9½ to 13 million cubic feet, was encountered at 1,010 feet, and an analysis of this gas is said to have shown more than 80 per cent of nitrogen. As the wells about two-thirds of a mile north and south of this well found no gas at this horizon, it is evident, however, that the gas-bearing area is very small.

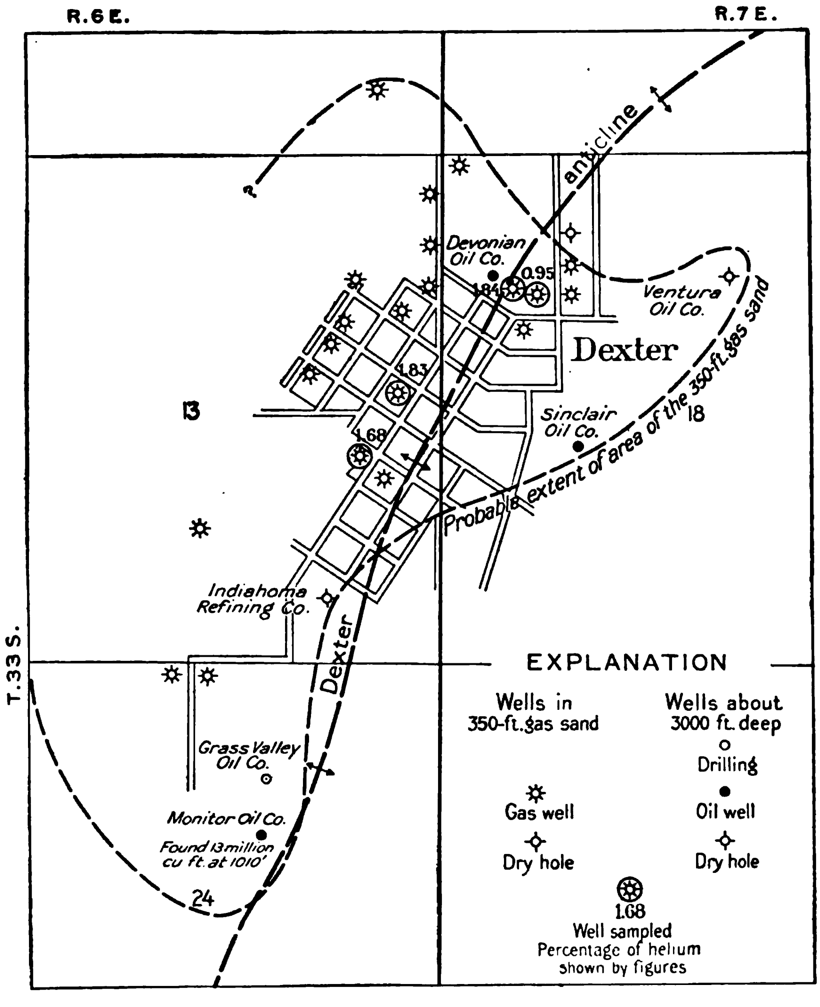

FIGURE 12.—Detailed map of the town of Dexter, Kans., showing location of wells sampled and helium content of gas.

AREA NEAR OTTO.

As shown in figure 11, several wells have been drilled about 6 miles south of Dexter, where there is a small dome on the crest of the main anticline. The southernmost of these wells found 2 million cubic feet of gas at a depth of 1,141 feet, and the three wells drilled farther north on the axis of the fold all found smaller volumes at about the same horizon. As the wells to the west found the sand filled with water, the productive area can not extend far down the flank of the fold, but it may extend some distance along the axis to the south. Two samples of this gas collected by the writer showed 1.9 and 0.5 per cent of helium. The poorer sample, however, is to be regarded with suspicion, for in the well from which it was taken the pressure was only a few ounces to the square inch, and the sample may have been contaminated with air. Apparently, therefore, this gas is exceptionally rich in helium, and it is believed that a moderate supply might be developed by further drilling toward the south.

AREA SOUTHEAST OF OTTO.

About three years ago two gas wells were drilled by the Standish Oil Co. in sec. 17, T. 35 S., R. 7 E., about 5 miles southeast of Otto. These wells encountered the gas at a depth of about 1,475 feet and had initial open flows of 4½ and 5 million cubic feet a day, with a rock pressure of about 500 pounds to the square inch. Samples of the gas from these wells showed 0.94 and 1.04 per cent of helium. According to A. E. Fath, who made a geologic examination of the fields for the Geological Survey, there are no structural features in the vicinity favorable to the accumulation of gas and there is little prospect of an extension of the producing area.

SEDAN DISTRICT.

GENERAL FEATURES.

Chautauqua County, in which the Sedan district is situated, has for many years ranked high among the oil-producing counties of Kansas, and the eastern and central parts of the county have now been thoroughly prospected. Two fair-sized gas fields, the Hale and Havana fields, have been developed in the eastern part of the county, and a number of small fields in the central part—the Sedan district—yield a moderate volume of gas. The many samples that have been collected and analyzed indicate that the gas in the eastern part of the county contains less than 0.5 per cent of helium but that practically all the gas occurring in the central part at depths shallower than 1,000 feet contains between 0.5 and 2 per cent. (See results of tests, p. 100.) The western part of the county is practically untested, but development is now proceeding toward the west, and it is probable that the helium-rich area will be found to extend a considerable distance in that direction.

The location of the Chautauqua County gas fields is shown on Plate I, and the structure section on that plate shows the approximate stratigraphic position of the samples analyzed. It is evident that the decrease in helium content toward the east is related to the geology, for the helium-rich gas at Sedan occurs in the Kansas City group and owing to the general westward dip of the strata this formation lies too close to the surface to be gas-bearing in the eastern part of the county. In that locality production is obtained from lower beds, which generally yield gas poor in helium. The easternmost field in which gas carrying as much as 0.5 per cent of helium has been found is the Monet field, about 5 miles east of Sedan.

The helium-rich gas of the Sedan district is high in nitrogen and thus too low in heating value to be in demand as a fuel, though owing to local conditions considerable volumes of it have been produced and used. The gas occurs above the oil horizons, however, and unless there happens to be a local demand for gas as fuel it is generally allowed to go to waste; in fact, as it interferes with drilling it is regarded by most operators as a nuisance. Because of these conditions accurate information as to the depth of a shallow gas and as to its volume and pressure is very difficult to obtain.

ROGERS POOL.

The Rogers pool lies just east of Rogers station on the Missouri Pacific Railroad, or chiefly in secs. 23–26, 35, and 36, T. 33 S., R. 10 E. (See fig. 13.) It consists of 41 gas wells, of which only 22 are now producing. As shown on the map, the pool is divided into two distinct portions by a strip of barren territory crossing secs. 25 and 26, in which 10 dry holes have been drilled.

The strata exposed in the vicinity of the Rogers pool belong to the lower part of the

Shawnee group and the upper part of the Douglas group. The Oread limestone, the highest formation of the Douglas, crops out in the southern part of the field. In the southern part of the pool the producing gas is encountered at depths of 700 to 800 feet and lies about 700 feet beneath the Oread, or near the middle of the Kansas City group. In the northern part of the pool, however, the producing sand lies at a slightly higher horizon, being encountered at depths of 650 to 750 feet, and in this district a gas sand at 350 to 450 feet is also reported by many wells.

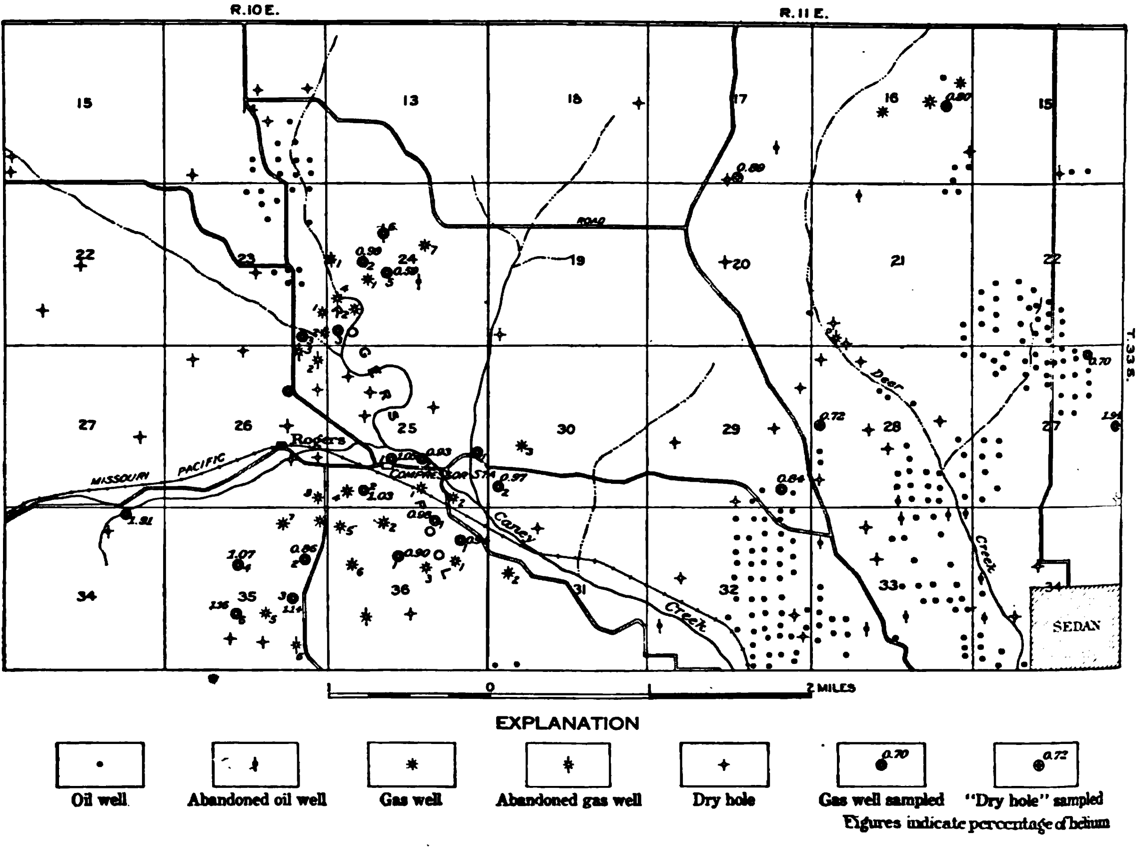

FIGURE 13.—Map of Sedan district, Kans. showing location of wells sampled and helium content of gas.

According to P. V. Roundy, who made a detailed geologic examination of the Sedan district, the Rogers pool is associated in a general way with a structurally high area or broad nose which centers in the SE. ¼ sec. 19 and extends to the SW. ¼ sec. 23. The limits of the producing area, however, are evidently determined by the porosity and continuity of the sand, for the barren strip that crosses the center of the field lies near the highest part of the uplift. Such conditions of course can not be determined from surface examinations, and drilling may prove the remainder of the uplift to be barren, but the areas that are structurally most favorable have not yet been adequately tested. The favorable areas include the N. ½ sec. 30, the W. ½ sec. 19, and all of sec. 24, and probably also the E. ½ sec. 13, the W. ½ sec. 18, and the SW. ¼ sec. 23. Production may also be extended farther west; the gas well in the NE. ¼ sec. 34, for example, which is drilled on a monocline, indicates that there is at least a small pool in that locality. It should be pointed out in this connection that too much weight can not be attached to the "dry" holes shown on the map, for these wells were drilled for oil, and moderate flows of low-pressure gas are generally saved only when there is a special need or market for them.

Structural features of the type described above occur throughout a large part of western Chautauqua County, and it is probable that many of them are associated with gas pools and that the gas occurring at depths of 900 feet or less for at least several miles west of Rogers is rich in helium.

The first wells in the Rogers pool were drilled in 1912, and by the end of 1913 18 wells, with a combined open flow of 63 million cubic feet a day and an average rock pressure of 221 pounds to the square inch, had been finished. The initial open flow of some of the wells was as much as 8 million cubic feet a day, though the average was about half that figure. By the summer of 1914 24 wells, having an average open flow of 2½ million cubic feet a day, were in operation. During 1914 the field produced only 1½ to 2½ million cubic feet daily, chiefly owing to the poor quality of the gas for heating. During the winter of 1915–16 the field was taken over by another gas company and was made to produce as much as 10 million cubic feet a day. Since that time the production has gradually declined until in August, 1918, it amounted to only about 1 million cubic feet daily. At that time the average daily open flow of the 22 producing wells was 260,000 cubic feet, their average rock pressure was 38 pounds to the square inch, and their combined daily open flow was a little less than 6 million cubic feet.

Although the foregoing figures indicate that the pool is now almost exhausted, it is believed that this condition is due partly to the fact that the gas commands so low a price that the well owners have not felt justified in going to much expense in keeping the wells in proper condition. The oil wells of Chautauqua County, though generally small, are remarkable for their long life, a feature evidently due to the fine grain of the oil sand and to the rather low gas pressure. Whether or not the gas sands in this area are also capable of unusually long continued production it will be impossible to say, for practically all the gas wells visited by the writer in the Sedan district had suffered from lack of attention. Despite this condition, however, many old wells have held up remarkably well, and there is reason to believe that the fields of the Sedan district would, with proper care, yield a moderate output for a long period.

It should not be inferred from the foregoing remarks that the Rogers pool itself can still be rejuvenated, though undoubtedly the production could temporarily be somewhat increased. So far as can be learned from a study of the structure, however, there is still good territory in the vicinity, and it is probable that the producing area could be somewhat extended. Moreover, there is every reason to suppose that similar pools could be developed in the central and western parts of the county and that their gas would prove equally rich in helium.

Two pipe-line samples of gas from the Rogers pool average 0.96 per cent of helium, and 14 samples from individual wells contained from 0.86 to 1.16 per cent. One sample showed only 0.59 per cent, but it may have been contaminated by air, and on the other hand gas from the well in the NE. ¼ sec. 34 (see fig. 13) showed 1.912 per cent. All these gases are from the sands between 650 and about 800 feet in depth, and the gas occurring at 350 to 450 feet in the northern part of the Rogers pool probably contains well over 1 per cent of helium.

The general character of the gas of the Rogers pool is shown by analysis 20, page 39.

AREA NEAR SEDAN.

Although practically no gas is now produced in the areas north of Sedan and between Sedan and the Rogers pool, it is stated on good authority that many of the oil wells in these areas encountered gas at shallow depths. A few samples of this gas, obtained mostly from abandoned and practically exhausted wells, showed a high content of helium. In the district south of Sedan a little gas is now being produced, but all of it is derived from the Peru sand, which lies about 500 feet beneath the helium-bearing sands of the Rogers pool and which yields gas carrying only about 0.4 per cent of helium. It is reported, however, that wells in several localities encountered gas at shallower depths, and it may be presumed that this gas contains more than 0.5 per cent of helium.

The richest gas occurs in a sand found at a depth of about 400 feet in the area north of Sedan. Several wells were finished in this sand some years ago to supply fuel for drilling oil wells, but because of the low pressure of the gas and its low heating value no care was taken of the gas wells, and most of them soon became exhausted. However, the Fleming & Wadsworth well, near the east quarter corner of sec. 27, which was drilled about 1907, is said to have had an initial daily open flow of 3 or 4 million cubic feet, and when visited by the writer in July, 1918, it still showed about half a million cubic feet, with a pressure of about 50 pounds to the square inch. The test of a sample of this gas showed 1.94 per cent of helium, and an analysis previously made by Prof. Allen showed 55.7 per cent of nitrogen. (See analysis 18, p. 39.) About a mile east of this well, in the southeast corner of sec. 26 and the southwest corner of sec. 25, T. 33 S., R. 11 E., three gas wells were drilled to the 400-foot sand about three years ago, but all of them are now practically exhausted. A sample from the well in the southeast corner of sec. 26 showed 1.04 per cent of helium. A dry hole in the NE. ¼ sec. 29 is reported to have passed a sand capable of yielding 2 or 3 million cubic feet of gas daily at a depth of about 400 feet, and several wells could doubtless be drilled in this locality. Two oil wells drilled several years ago just outside the limits of Sedan, near the center of sec. 3, are reported to have found a sand yielding 3 or 4 million cubic feet of gas a day at a depth of 212 feet. This sand is probably equivalent to the 400-feet sand north of Sedan, and there is every reason to suppose that the gas is very rich in helium.

It is not to be inferred from the foregoing statements that all the area for 2 or 3 miles north of Sedan is thought to be underlain by the shallow gas. It is even impossible to state that all the wells referred to draw from the same horizon, though this is highly probable; but it is very evident that the sand is either discontinuous or is productive only locally. It is impossible to predict in advance of drilling how much of this gas could be obtained, but it seems highly probable that a yield of at least 1 or 2 million cubic feet a day could be maintained for a period of two or three years.

A deeper sand, probably equivalent to that found in the Rogers pool, is also encountered in the area north and west of Sedan at a depth of 600 to 700 feet, and in some localities gas is found also in sands at 900 and 1,000 feet. The relation of the sands in this area is shown by the following well log:

Log of Allen McIntosh well No. 1, in the southeast corner of the SW. ¼ NE. ¼ sec. 16, T. 33 S., R. 11 E.

	Feet.
Soil	0-3
Shale, black	3-63
Lime, Oread	63-83
Shale, red	83-140
Sand; three bailers of water	140-150
Shale, black	150-160
Sand; hole full of water	160-280
Shale, black	280-410
Sand	410-430
Shale, black	430-455
Sand	455-465
Shale, black	465-708
Sand, hard; gas	708-712
Sand, soft	712-720
Shale, black	720-765
Lime, white	765-768
Shale, black	768-908
Sand; gas	908-920
Shale, white	920-945
Sand	945-955
Shale	955-960
Lime	960-962
Shale, black	962-972
Sand; "Salt sand"	972-1,072
Shale, black	1,072-1,077
Shale	1,077-1,130
Lime	1,130-1,140
Sand; "Stray sand"	1,140-1,162
Shale, black	1,162-1,172
Lime	1,172-1,177
Shale, black	1,177-1,283
Sand, hard; "Peru sand"	1,283-1,289
Shale, black	1,289-1,313

Five samples of gas from the sands encountered at depths of 700 to 900 feet were collected in the area north and west of Sedan, and their helium content was found to range between 0.70 and 0.89 per cent. The wells sampled are in secs. 16, 17, 27, 28, and 29, T. 33 S., R. 11 E., and their location is shown on figure 13. The well in sec. 29 still has an open flow of about half a million cubic feet a day, but the other wells are practically exhausted. The gas has been reported in many oil wells, however, and there is no doubt that a moderate production could be developed. As already stated, all this gas is too low in heating value and too irregular in distribution to permit producing it at a profit for use as fuel, but as a source of helium its value should be sufficient to warrant the necessary expense.

MONETT FIELD.

In the vicinity of Monett (see Pl. I) gas has been produced for many years, chiefly from the Salt sand but in part from deeper sands. The Salt sand in this district is found at a depth of 500 to 600 feet. Some of the wells had an initial daily open flow of 3 million cubic feet, though all of them are now very small. The town of Sedan is supplied by half a dozen wells in secs. 28, 32, and 33, T. 33 S., R. 12 E., the combined daily production of which is now less than a million cubic feet. A sample of the Salt sand gas showed 0.57 per cent of helium.

This gas has not been systematically developed, being undesirable because of its rather low pressure and its low heating value; and it is believed that if necessary a production of 2 or 3 million cubic feet a day could be developed and could be maintained for two or three years. Though the helium content of this gas is lower than that of the gas to the north and west of Sedan, it is higher than that of the other gases within a radius of 35 miles. The Monett gas could be rather cheaply produced, and if an extraction plant were erected in the Sedan district it might prove desirable to treat the Monett gas in connection with the richer product of the Rogers and Sedan fields.

FIELDS IN OSAGE COUNTY, OKLA.

PEARSON FIELD.

The Pearson field is in the central part of Osage County, Okla., principally in secs. 10 to 20, T. 27 N., R. 8 E., on the Midland Valley Railroad. In July, 1918, the Pearson field contained 17 producing wells having an average rock pressure of about 125 pounds to the square inch and a total open flow of about 40 million cubic feet a day. The production of the field during May amounted to 146 million cubic feet, or an average of 4.7 million cubic feet daily, though it is believed that with some additional drilling 10 or 15 million cubic feet a day could easily be produced.

Most of the gas produced in the Pearson field is obtained from sands lying at depths between 750 and 1,000 feet, although several wells recently drilled derive their gas from a sand at about 1,450 feet. The main producing sand lies 100 to 400 feet below the Oread limestone, of the Douglas group and therefore near the base of the Douglas or the top of the Lansing group. According to A. E. Fath, it is roughly equivalent to the sand in the Otto district, Kans., which yields gas carrying about 1 per cent of helium. The structural geology of the Pearson district and of the area to the north has been investigated by K. C. Heald,[42] who finds that the field is on a well-defined though irregular anticline, the highest point of which appears to be in the southeast corner of sec. 30, T. 27 N., R. 8 E. In this vicinity there are also several minor domes, at least one of which has proved productive.

As shown by the 12 analyses on page 104, the Pearson gas ranges in helium content between 0.23 and 0.71 per cent, the average as determined by three tests of pipe-line gas being about 0.50 per cent. The gas occurring in the uppermost sands appears to be somewhat richer in helium than that in the lower part of the producing zone.

The general quality of the Pearson gas is shown by the first analysis in the table on page 82.

MYERS FIELD.

The Myers field is about 6 miles southeast of the Pearson field, in the northeast corner of T. 26 N., R. 8 E. In July, 1918, the field contained 10 wells having an average rock pressure of about 240 pounds to the square inch and a total open flow of about 15 million cubic feet a day. During May the average daily production was 1,392,000 cubic feet, or only about 9 per cent of the open flow.

The Myers gas is derived from two sands, the shallower lying at a depth of about 550 feet and the deeper at a depth of about 1,150 feet. These sands are believed to be equivalent to those that are productive in the Pearson field. Although flows as high as 5 million cubic feet a day are found in the shallower sand, the pressure is low, and in July, 1918, all but two of the wells had been deepened to the 1,150-foot sand.

The field is on a small dome or anticline similar to that from which the gas at Pearson is produced. The wells already drilled apparently define this dome, but there are other structural features of the same type in the vicinity which when developed will doubtless furnish a large volume of gas.

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[42] Geologic structure of the northwestern part of the Pawhuska quadrangle, Okla.: U. S. Geol. Survey Bul. 691, pp. 82, 89, 1918.

A pipe-line sample of the Myers gas was found to contain 0.37 per cent of helium, and three samples from individual wells carried 0.27, 0.35, and 0.43 per cent. (See p. 104.) The helium content of the Myers gas is thus distinctly lower than that of the gas of the Pearson field, though the gas is believed to occur at about the same horizon. As shown by the third analysis in the following table, the Myers gas is considerably lower in nitrogen than the Pearson gas:

Analyses of gas from the Pearson and Myers fields, Oklahoma.

	Pearson field, gas at 900 feet.	Myers field.	
		Gas at 317 feet.	Gas at 1,150 feet.
Carbon dioxide (CO_2)	0.00	0.25	0.86
Oxygen (O_2)	.21	.12	.00
Methane (CH_4)	51.91	76.60	58.60
Ethane (C_2H_6)	1.12	2.25	5.69
Residue (N_2, etc.)	46.86	20.78	34.85
	100.00	100.00	100.00
Heating value (British thermal units)	520	778	664

In sec. 23, T. 26 N., R. 9 E., about 5 miles southeast of the Myers field proper, large volumes of shallow gas are reported. A deep well in that locality is said to have encountered a sand yielding 6 million cubic feet a day at a depth of 317 feet, one yielding 3 million cubic feet at a depth of 410 feet, and one yielding 2 million cubic feet at a depth of 660 feet. This gas was not tested for helium, but, as shown by the second analysis in the above table, the gas at 317 feet carries 20.78 per cent of nitrogen and is probably at least as rich in helium as the gas in the main Myers field.

PROSPECTIVE FIELDS IN WESTERN OSAGE COUNTY.

The eastern part of Osage County comprises some of the richest oil and gas territory in the Mid-Continent region, but that portion lying west of the Pearson and Myers fields is practically undeveloped. This condition is due chiefly to the fact that the lands throughout the county are the common property of the Osage Tribe, and the leasing of the lands for oil and gas development has therefore been strictly controlled by the Government. During the last year or two, however, a great many leases in the western Osage country have been sold, and within a short time a number of pools will doubtless be discovered.

Production in the eastern part of Osage County and in Washington, Nowata, and Rogers counties, still farther east, is obtained from sands beneath the "Oswego lime," or chiefly in the Cherokee shale. As shown by many analyses, the Cherokee gas is characterized by rather low nitrogen content, and therefore only a few samples of it were tested for helium. None of these samples contained more than 0.1 per cent. The location of the principal gas fields in this region and data as to the helium or nitrogen content of the gas are shown on Plate I.

Because of the prevailing westerly dip the Cherokee sands lie at considerable depths in the western part of Osage County, but higher sands which are productive elsewhere in northern Oklahoma and southern Kansas lie at moderate depths. The geology of the western Osage country has been examined in detail by members of the Geological Survey,[43] and a great many small folds of the type that has proved so productive farther east have been found. There is therefore no reason to doubt that the western Osage country will yield large volumes of gas and that a number of fields similar to those at Pearson and Myers will be developed in this region.

From all the information at hand it appears that at least the northwestern part of Osage County should be productive of gas fairly rich in helium. The gas-bearing zones which occur at shallow depths in the western part of Osage County are equivalent to those which contain helium-rich gas in Chautauqua County and the eastern part of Cowley County, Kans. The district near Otto, Kans., for example, in which the gas contains 1 per cent of helium, lies only about 2 miles from the northern edge of Osage County and directly along the strike of the rocks. Moreover, the fact that the Myers field produces gas averaging about 0.4 per cent of helium and the Pearson field, about 6 miles to the west, produces gas averaging at least 0.5 per cent, suggests a progressive increase in helium content toward the west. It is therefore believed that gas containing at least 0.75 per cent of helium will be encountered in the northwestern part of Osage County at fairly shallow depths and that in all probability large volumes of such gas will be available. So far as can be judged this area comprises the best prospective helium territory in the United States.

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[43] White, David, and others, Structure and oil and gas resources of the Osage Reservation, Okla.: U. S. Geol. Survey Bull. 686 (in press).

OTHER MID-CONTINENT FIELDS.

In addition to the fields already described, which are noteworthy as present or prospective sources of gas fairly rich in helium, there are many districts in the Mid-Continent region that yield small volumes of helium-rich gas or large volumes of gas containing only about 0.25 per cent of helium. The location and helium content of these supplies are shown on Plate I, and data regarding the volume of the gas, the depth from which it is obtained, etc., are given in the tables at the end of this report.

MINOR FIELDS IN KANSAS.

Cady and McFarland in 1906 found a number of gases that contained more than 0.25 per cent of helium; in fact, as shown on Plate I, all the Kansas gases examined appear to contain measurable proportions of helium, and the average content of all the gas that has been produced in the State is probably more than 0.15 per cent. Many of the fields investigated by Cady and McFarland are now, however, practically exhausted, for the gas resources of Kansas have been heavily drawn upon in the last 15 years, and since 1908 there has been a great decline in production. (See fig. 14.) A temporary increase was recorded in 1915–16, owing chiefly to the discovery of the Eldorado and Augusta fields, but production fell off again in 1917–18, and there seems to be small prospect of any notable increase in the future.

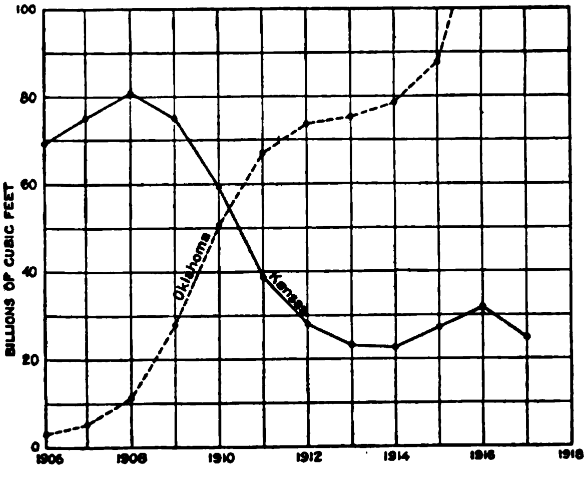

FIGURE 14.—Diagram showing production of natural gas in Kansas and Oklahoma.

One of the richest gases reported by Cady and McFarland was that from Eureka, in Greenwood County, two samples of which were found to carry 1.50 per cent of helium. The Eureka field was investigated in 1918 and was found to be practically exhausted, though a sample was collected and found to contain 1.42 per cent of helium. The Moline and New Albany fields in Elk County, and the Burlington field, in Coffey County, all of which produce gas carrying about 0.5 per cent of helium, and the Fredonia field, in Wilson County, which yields gas carrying about 0.6 per cent, furnished considerable volumes of gas in 1906 but now produce only an insignificant supply. The same is true of the Buffalo, Altoona, and Neodesha fields, in Wilson County, and the Chanute field, in Neosho County, all of which produce gas carrying about 0.3 per cent of helium; and of the Spring Hill field, in Johnson County, and the Garnett field, in Anderson County, which yield gas carrying about 0.4 per cent.

A number of fields have of course been discovered in Kansas since Cady and McFarland made their survey, but all of them except the Eldorado, Augusta, Otto, and Sedan fields are either small or yield gas rather poor in helium. The Beaumont field, in the southwestern part of Greenwood County, is perhaps the most promising, for it yields gas containing 0.86 per cent of helium. Although in July, 1918, there was only one gas well in this field, considerable volumes of gas were reported in all the surrounding oil wells, and it is probable that a production of several million cubic feet a day could be developed. A small supply of gas carrying 0.65 per cent of helium has also been recently found near Virgil, and a larger supply containing 0.36 per cent near Toronto, Greenwood County. Near Winfield, Cowley County, there is an old field which is still capable of producing almost a million cubic feet a day of gas carrying 0.38 per cent of helium.

In Elk and Chautauqua counties several fields have recently been discovered that yield gas carrying more than 0.33 per cent of helium. Near Longton and Oak Valley, in the southeast corner of Elk County, there are two small pools of shallow gas containing 0.55 and 0.40 per cent of helium. In September, 1918, each of these pools was producing about 1 million cubic feet a day, and the supply could doubtless be increased by further drilling. A large volume of deep gas was also discovered in 1918 near Oak Valley, but it contains only 0.001 per cent of helium. The gas of the Hale and Havana fields, in the eastern part of Chautauqua County, averages about 0.36 per cent of helium, and in September, 1918, these fields were together producing about 10 million cubic feet a day. This supply can doubtless be increased. Most of the gas produced in the Chautauqua field, in the southern part of the county, is derived from deep sands and contains very little helium, but a small supply of gas is also obtained at a depth of 600 to 800 feet, and this carries 0.21 to 0.43 per cent.

MINOR FIELDS IN OKLAHOMA.

As shown in figure 14, Oklahoma produces a very large quantity of gas annually, and since 1906 the production has steadily increased. In 1917 Oklahoma furnished about 137 billion cubic feet and became the second largest gas-producing State in the Union. As shown on Plate I, however, the Oklahoma area of gas containing more than 0.5 per cent of helium is practically confined to the northwestern part of Osage County, whereas a very large proportion of the gas produced in Oklahoma is obtained from fields east of that area and from those in the southern part of the State. The average helium content of Oklahoma gas is therefore exceedingly small, and only a few fields outside of the western part of Osage County deserve special mention.

As pointed out on page 40, the shallow gas produced in the western part of the northern Oklahoma petroleum region is characteristically rich in nitrogen but poor in helium. For example, in the Pearson gas the ratio of nitrogen to helium is probably almost 100, and it attains a similar value in several other Oklahoma gases, whereas in the rich Kansas gas the ratio is usually less than 50. In other words, a Kansas gas containing 50 per cent of nitrogen is likely to carry about 1 per cent of helium, whereas an Oklahoma gas carrying the same proportion of nitrogen may contain only 0.5 per cent of helium. High-nitrogen gases have been found at many localities in the western parts of Osage and Pawnee counties and in Payne, Noble, and Kay counties, Okla., but it must be borne in mind that a high-nitrogen gas in this district is not necessarily a gas rich in helium.

The Pearson and Myers fields, in Osage County, have already been described, and the prospective importance of the western Osage country as a source of helium-bearing gas has been pointed out. The only other field yet developed in the Osage region that may be of value as a source of helium is the Hominy field, which lies about 25 miles south of Pearson. This is primarily an oil field, but most of the wells report large volumes of gas at depths of about 500 feet. This gas has been cased off, but a few wells have been finished in a gas sand at about 1,000 feet. Three analyses of Hominy gas, probably that from the 1,000-foot horizon, show 15 to 20 per cent of nitrogen, and it is probable that the 500-foot gas is still higher in nitrogen and may therefore contain enough helium to be of commercial value.

The Blackwell field, in the northern part of Kay County, is one of the largest gas fields in Oklahoma. Its productivity is due chiefly to the large number of gas-bearing sands present; one well, for example, encountered eight gas sands between 692 and 3,200 feet, the combined open flow of which was 116 million cubic feet daily.[44] Because of the large volumes of gas available in the Blackwell field and the fact that some of it occurs at shallow depths, six samples of the gas from different sands were tested for helium, but the highest content found was only 0.27 per cent.

The Ponca City field, in the southern part of Kay County, produces a considerable quantity of oil and formerly yielded large volumes of gas, but the gas resources are now almost exhausted. The gas occurs chiefly at a depth of about 500 feet, and the sand is regarded as about equivalent to the 950-foot sand at Blackwell and more than 1,000 feet stratigraphically higher than the producing sands of the Pearson and Myers fields. An analysis of the gas by Prof. Allen showed 40.1 per cent of nitrogen, but the helium content of gas from the same well proved to be only 0.36 per cent.

The Billings field, in the northern part of Noble County, is chiefly an oil field, though large volumes of gas are encountered at depths of 400 to 1,100 feet, and a little of this gas is produced to supply the local demand. A sample of gas occurring in Permian strata at a depth of 500 feet contained, however, only 0.10 per cent of helium, and a sample from a sand at 1,036 feet was found to carry 0.39 per cent. As shown by analysis 21, on page 39, this gas contains 42.5 per cent of nitrogen.

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[44] Petroleum and natural gas in Oklahoma: Oklahoma Geol. Survey Bull. 19, p. 272, 1917.

The Morrison field, in the western part of Pawnee County, has produced large volumes of gas, though the output is now declining. The gas occurs at a depth of about 2,000 feet and carries 22 to 25 per cent of nitrogen but only about 0.24 per cent of helium.

The Ingalls field, about 10 miles east of Stillwater, Payne County, contains only half a dozen oil and gas wells and is of interest chiefly because of the high nitrogen content of the gas and because of the large flows reported. In the first gas well a flow estimated at 21 million cubic feet of gas a day was found at 650 feet, another of 57 million cubic feet at 1,760 feet, and one of 30 million cubic feet at about 3,200 feet. The shallow gas was cased off, but the gas at 1,760 feet was produced for about a year. Analyses of this gas showed from 50 to 54 per cent of nitrogen, and a sample which is thought to represent the same gas contained 0.35 per cent of helium. A sample from a deeper sand carried only 0.05 per cent of helium. It was not possible to obtain a sample of the 650-foot gas, which is doubtless richer in helium than that at 1,760 feet, but it is believed that no great supply of either of these gases can be developed.

A small supply of gas said to contain 30 per cent of nitrogen has been found about 7 miles south of Bristow, Creek County, but this gas proved to contain only 0.15 per cent of helium.

Large volumes of gas are now produced in southern Oklahoma, and further supplies will doubtless be discovered in that region. All the existing sources in southern Oklahoma have been sampled, however, and have proved to be very poor in helium. (See Pl. III and p. 27.)

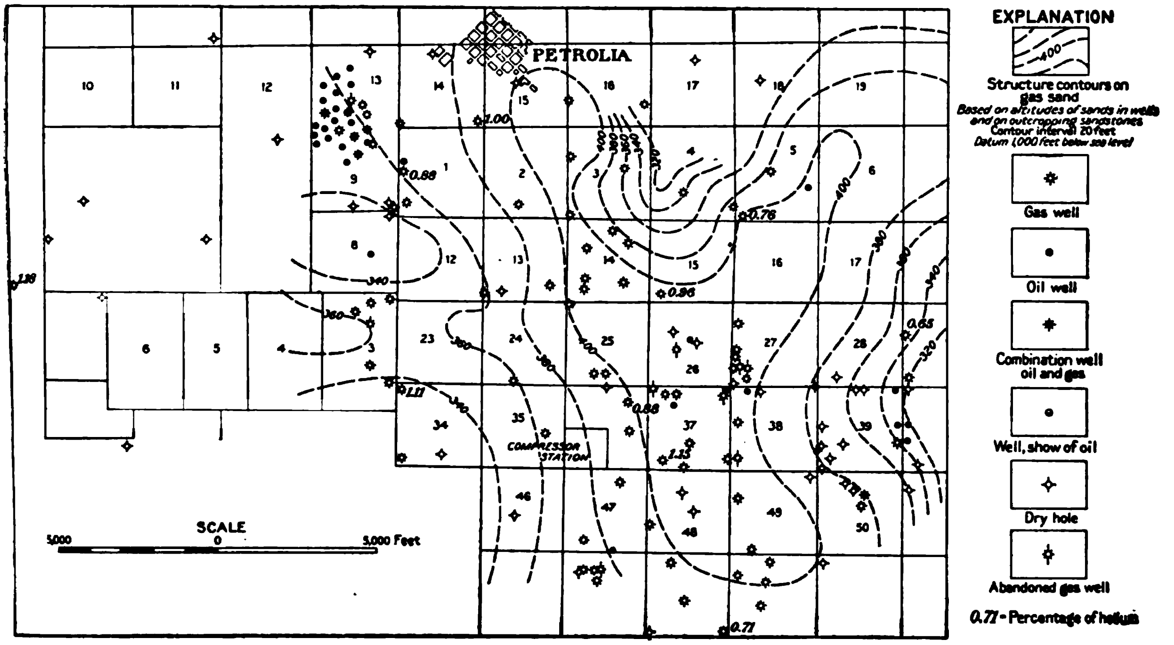

FIGURE 15.—Map of Petrolia field, Tex., showing location of wells sampled and helium content of the gas.

NORTH TEXAS REGION.

PETROLIA FIELD.

LOCATION AND EXTENT.

The Petrolia field, which is in the northern part of Clay County, Tex., contains at present the largest available supply of helium-bearing gas and has in fact furnished all the helium so far produced by the Government. The field lies about 16 miles northeast of the city of Wichita Falls, with which it is connected by the Wichita Valley Railroad. In the north end of the field is the town of Petrolia, and about 2½ miles south of the town is the Government plant for extracting helium. (See fig. 15.)

The field is elliptical in shape, extending about 3½ miles from northeast to southwest and about 4 miles from northwest to southeast. In June, 1918, there were some 350 wells in the

Petrolia field, but about 250 of them are oil wells, averaging only 300 feet in depth. The gas-bearing beds lie at a depth of 1,550 to 1,750 feet and in places carry some oil. Of the wells drilled to this horizon about 65 found gas in commercial quantities, and about 35 found oil. The limits of the field are now pretty well defined by dry holes.

GEOLOGIC OUTLINE.

The surface rocks in the Petrolia field belong to the Wichita formation, of Permian age. These beds extend to a depth of 1,000 feet or so, and the deep oil and gas probably occur in the Cisco formation, of upper Pennsylvanian age.

As shown in figure 15, the field is on the crest of an irregular anticline, the long axis of which within the field trends about north-northwest. According to Shaw,[45] there is probably, however, a branch anticline or nose extending to the northeast, and a similar nose extending to the northwest. The best production has in general been obtained from the highest part of the main anticline, although there are many local irregularities caused by variations in the porosity of the sand.

Commercial supplies of gas are apparently confined to a group of beds which in the center of the field lie at depths of 1,500 to 1,750 feet. A study of the well logs indicates that there are two fairly persistent sands, or groups of sands—one lying at a depth of about 1,550 feet and the other at about 1,700 feet. A gas zone intermediate between these two is also reported in most wells, and there are in addition a number of "stray" sand lenses. All the individual sands are discontinuous and irregular, however, and can be traced only for short distances. In most of the wells the sands at the three main horizons are all more or less productive, but a few wells have found gas only in the lower group of sands. On the other hand, some of the wells, especially the earlier ones, stopped in the upper or middle sands, and the lower ones have not been tested.

The general character of the gas-bearing beds is shown in the following partial logs:

Typical logs of wells in the Petrolia field, Tex.

Stine Oil & Gas Co., Stine well 1.	Feet.	**Lockridge well 1.**	Feet.
Water sand	1,322-1,348	Shale	1,165-1,200
Blue shale	1,348-1,365	Black shale	1,200-1,285
Red rock	1,365-1,372	Dry sand	1,285-1,300
Blue shale	1,372-1,470	Shale	1,300-1,305
White slate	1,470-1,551	Sand	1,305-1,315
Sand (dry, but probably represents upper gas sand in other wells).	1,551-1,555	Blue shale	1,315-1,463
Shale	1,555-1,682	Gas sand	1,463-1,473
Sandy shale	1,682-1,694	Red rock	1,473-1,485
Gas sand	1,694-1,708	Gas sand	1,485-1,490
Blue shale	1,708-1,719	Slate and shells	1,490-1,529
Gas sand (16 million cubic feet)	1,719-1,731	Gas sand	1,529-1,539
Blue shale	1,731-1,739	Slate	1,539-1,567
Broken sand	1,739-1,744	Gas sand	1,567-1,577
Blue shale	1,744-1,750	Slate	1,577-1,606
Sand shale	1,750-1,752	Gas sand	1,606-1,624
Red shale	1,752-1,755	Slate	1,624-1,648
Blue shale	1,755-1,757	Gas sand	1,648-1,660
Broken sand	1,757-1,763		
Blue shale	1,763-1,783		

QUALITY OF THE GAS.

Since the Government began operations in the Petrolia field the helium content of the gas has been repeatedly determined and appears to average about 0.93 per cent. The proportion of helium is not constant from week to week, however, but varies by as much as 0.1 per cent. This is shown by the following tests made by different chemists over a period of six months:

Tests of the helium content of Petrolia gas.

Date (1917).	Chemist.	Per cent of helium.
June 13	H. P. Cady	0.88
Oct. 8	do	.86
Oct. 30	Moore & Yancey	.966
Do	H. P. Cady	.89
Nov. 6	J. C. Satterly	.95
Nov. 15	do	.93
Nov. 19	H. P. Cady	.945
Nov. 23	J. C. Satterly	.92
Nov. 19	H. P. Cady	.954
Dec. 11	do	.985

These tests show an apparent increase in helium content from month to month, but whether this is a regular increase that is likely to continue or simply a fortuitous variation due to analytical error or to unexplained natural causes is not clear.

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[45] Shaw, E. W., Matson, G. C., and Wegemann, C. H., Natural-gas resources of parts of north Texas: U. S. Geol. Survey Bull. 629, pp. 25-41, 1916.

The tests of 10 samples of gas from individual wells given on page 86 show a range in helium content between 0.65 and 1.18 per cent, and the gas in the uppermost group of sands seems to be somewhat richer than that in the others. There is, however, no marked and constant difference in helium content between gases from different parts of the producing zone, and there appears to be no possibility of segregating the richest gas.

The general quality of the Petrolia gas is shown by the following analyses:

Analyses of gas from the Petrolia field.

	1	2	3	4
Carbon dioxide (CO_2)....	0.2	0.2	0.0	0.0
Oxygen (O_2)............	.0	.0	.0	.0
Methane (CH_4)..........	48.4	52.7	51.1	51.5
Ethane (C_2H_6)..........	12.8	9.3	10.0	10.2
Nitrogen[a] (N_2)..........	38.6	37.8	38.9	38.3
	100.0	100.0	100.0	100.0
Heating value (British thermal units per cubic foot at 0° C. and 760 millimeters pressure)...	755	734	730	738
Specific gravity..........	0.78	0.76	0.76	0.76

[a] Includes helium.

1,2. Cited from U. S. Geol. Survey Bull. 629, p. 41, 1916. 1. Gas from Matlock well 1, which supplies Petrolia; analysis by G. A. Burrell, Bureau of Mines. 2. Gas from Beatty well 1; analysis furnished by Lone Star Gas Co.

3,4. Pipe-line samples of Petrolia gas, collected in September and October, 1914, at Fort Worth, Tex., and analyzed by the Bureau of Mines. Cited from Bureau of Mines Tech. Paper 109, p. 7, 1915.

PRODUCTION OF THE FIELD.

The first gas well in the Petrolia field was drilled in October, 1907, and was reported to have had a 4-minute pressure of 470 pounds to the square inch and a capacity of 8 to 10 million cubic feet a day. Most of the other early wells, however, had initial pressures of 600 to 740 pounds and open flows of 10 to 40 million cubic feet. Most of the recent wells have come in with pressures of 200 to 300 pounds and flows of 2 to 15 million cubic feet. The average pressure of all wells in the field on June 1, 1918, was 82 pounds, and the average open flow on January 1, 1918, was 1,686,000 cubic feet.

About 65 successful gas wells have been drilled in the field, and 53 of them are now producing. Nine of the thirteen wells drilled in 1909 are still producing, though during 1917 about a dozen wells were exhausted and abandoned. Nearly all the producing wells were drilled by oil companies in the search for oil, and in many wells much gas was wasted before the well was taken over by the gas company.

The following table gives statistics of the decline of rock pressure and open flow and also the quantity of gas marketed by the Lone Star Gas Co. The figures showing production for 1916 and especially for 1917 are low, for during these years much gas was lost through pipe-line leaks. The total gas marketed by the Lone Star Co. to date is about 60 billion cubic feet, and it is probable that nearly 10 billion cubic feet has been marketed by other companies. It seems safe to assume that 20 billion cubic feet has been used for fuel in the field, wasted in drilling or repairing wells, and lost through pipe-line leaks, making a total of approximately 90 billion cubic feet removed from the sands.

Rock pressure, open-flow capacity, and partial production of Petrolia field, 1910–1918.

Year.	Average rock pressure Jan. 1 (pounds per square inch).	Open flow on Jan. 1.			Gas marketed by Lone Star Gas Co. (M cubic feet).
		Number of wells tested.	Combined open flow (M cubic feet).	Average per well (M cubic feet).	
1910........	....	......	....	....	1,583,080
1911........	....	......	....	....	5,175,196
1912........	659	......	....	....	7.186,322
1913........	621	......	....	....	10,089,135
1914........	511	......	....	....	9,683,293
1915........	318	41	365,090	8,904	8,999,837
1916........	239	43	272,345	6,484	8,945,522
1917........	174	46	190,503	4,141	6,101,167
1918........	87	45	75,855	1,686	....

DURATION OF THE SUPPLY.

Figure 16 shows graphically the decline of average rock pressure and the number of wells producing by months from 1912 to 1918. The decline of average open-flow capacity from January 1, 1915, to January 1, 1918, is also shown. The curve sketched in the diagram indicates that the pressure will reach zero in 1921. However, as the form of the curve for past years has been determined partly by the production of the field, which reached 45 million cubic feet on certain days during the winter of 1917–18, it is evident that if the production of the field were reduced to 12 or 15 million feet a day the curve would flatten and the field's life would be extended by a number of months.

Any new wells drilled in largely exhausted territory will tend to steepen the curve, unless production is held back, but wells drilled in relatively undepleted areas will, if successful, raise and flatten the curve. It will doubtless also be possible to reduce the line pressure below atmospheric pressure and thus extend the field's life beyond the point indicated.

In 1916 Shaw[46] estimated the original volume of gas in the Petrolia field to be 120 billion cubic feet, using the following factors: Area of the field, 15 square miles; average thickness of sand, 30 feet; porosity of sand, 20 per cent; and original rock pressure, 725 pounds to the square inch. In 1918 the writer made an independent estimate on the basis of somewhat different factors but arrived at the same figure. If we assume for the moment that the decline in rock pressure is an exact index of the decrease in volume of gas in the sand, and accept 120 billion cubic feet as the original volume, it is obviously possible to calculate the amount remaining in the sands at any given date. For example, in July, 1918, when the average rock pressure was 82 pounds to the square inch, it would appear that about 13½ billion cubic feet of gas remained in the sands, or a supply of 15 million cubic feet a day for 2½ years. This is somewhat lower than the estimate based on the curve showing decline in pressure and is also lower than would be expected from the estimate of the total gas marketed and wasted (90 billion cubic feet). The discrepancy may be due to the fact that the field contains several areas which are probably productive but which have never been drilled and in which, therefore, the pressure is considerably above 82 pounds to the square inch. If these areas prove to be productive, the true average pressure for the field in July, 1918, was probably over 100 pounds, and the quantity of gas remaining was probably nearer 25 billion cubic feet.

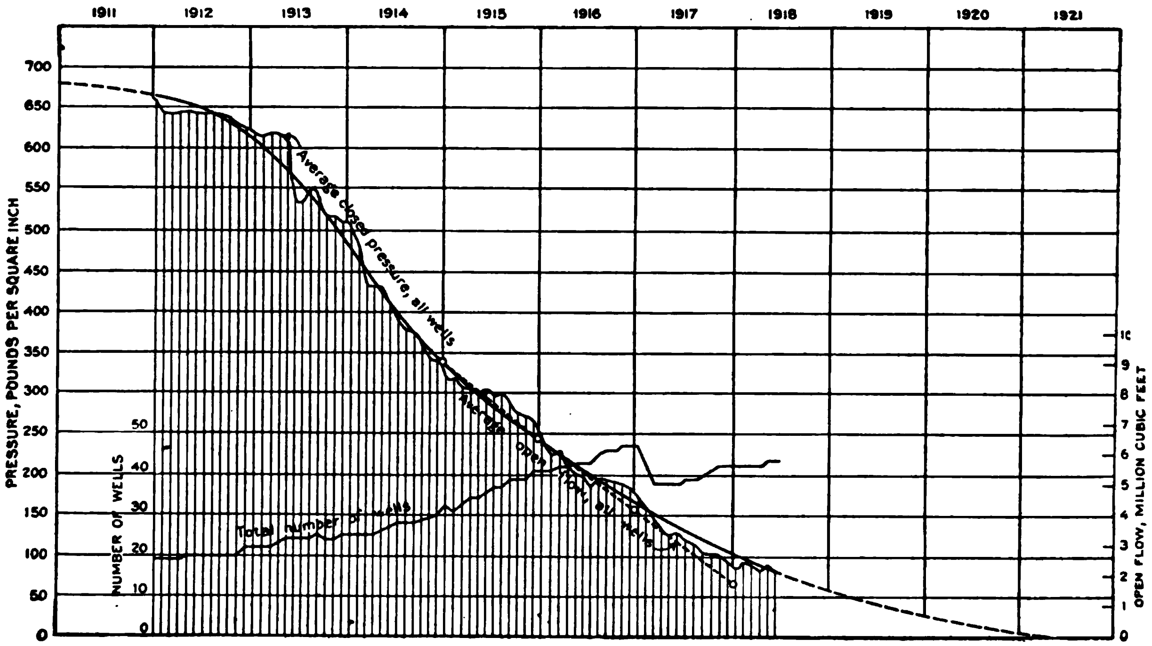

FIGURE 16.—Curve showing average closed pressure and average open flow of gas wells of Lone Star Gas Co. in the Petrolia field, Tex.

On the other hand, it must be recognized that the foregoing method of estimating the volume of gas remaining is likely to give results somewhat too high, for it is based on the assumption that the decline in rock pressure is due wholly to the removal of gas and is not affected by other conditions. If the pressure is being partly maintained by water in the sands, which migrates up the dip as the gas is removed, it is evident that the calculated volume of gas may be considerably greater than the true volume. In the Petrolia field there are some indications that water may be following the gas up the dip and thus maintaining the pressure to some extent, though water troubles have not been serious. Most of the old wells show some water, but it is probably top water that is leaking down behind the casing rather than water in the gas sands.

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[46] Op. cit., pp. 36-40.

POSSIBILITY OF EXTENSIONS OF THE FIELD.

Although the two foregoing estimates agree in placing the life of the field at two and one-half to three years from the middle of 1918, experience in other areas indicates that several factors tend to prolong the life of a field somewhat beyond the period estimated. Few if any fields are known that were capable of supplying as much as 45 million cubic feet a day against positive line pressure in the third year before their complete exhaustion. The chief factors tending to prolong the life of a field are the probability of discovering small extensions of the field and the tendency in the later part of the life of a field toward more efficient conservation and toward the utilization of small flows.

The Petrolia field is now pretty well bounded by dry holes, and there is no reason to expect any important extension of the producing area, but there are several small undrilled districts which appear promising. The largest of these is the supposed branch anticline on the northeastern slope of the main fold, which includes at least a square mile of undrilled territory. (See fig. 15.) Another possible area is at the south edge of the field, in blocks 61, 71, and 72. There are several wells in this area listed as dry holes, but at least one of them is reported to have had a daily capacity of about 7 million cubic feet. In the western part of the field there is also a strip of territory about half a mile wide and 1½ miles long, which has not been properly tested. Finally, there is a possibility of finding a small pool of gas about 2 miles west of the main field. An old well about a mile west of the field has been producing enough gas to furnish fuel for drilling wells for years. About a mile still farther west is a group of oil wells about 1,000 feet deep and one gas well which found a sand yielding 6 million cubic feet a day at a depth of 1,671 feet, or about the horizon of the gas sands in the main field. The gas from this well was sampled and found to contain 1.18 per cent of helium.

The chance of increasing the supply by finding deeper sands, however, is not particularly promising, as a number of deep wells on the outskirts of the field have encountered a great thickness of hard, water-bearing limestone at a depth of about 2,000 feet. There are, however, about eighteen gas wells within the field which do not penetrate the entire gas-bearing zone, and these wells could doubtless be improved by deepening.

Aside from the probability of extending the field, the effects of rigid conservation should be considered. The Petrolia gas is too high in nitrogen to be entirely satisfactory as a fuel, but it is rich in the higher hydrocarbons, which are condensed as gasoline, and it also has a special value as a source of helium. For these reasons it should be possible with the powerful compressor plant already installed to handle profitably wells with flows as low as half a million cubic feet a day; and whether many large wells can yet be brought in around the edges of the field or not, it is fairly certain that a number of such small wells can be developed. Moreover, the value of the gas justifies every precaution to reduce the waste of gas during drilling, as well as to keep the wells operating at the highest standard of efficiency.

OTHER FIELDS IN NORTHERN TEXAS.

In 1916, when a careful survey of the gas resources of northern Texas was made by Shaw and Matson,[47] the only large fields were the Petrolia and Mexia-Groesbeck fields. Since that time, however, the great oil and gas pools in the Ranger region have been discovered, and an enormous potential production of gas has already been developed. All sources of supply in the Ranger region and elsewhere in northern Texas were sampled in the summer of 1918, but none of the gases were found to be rich in helium. None of these gases, however, occur at the horizon of the Petrolia gas, and as the limits of the producing areas are still undefined and prospecting is still active it is possible that supplies of helium-rich gas will yet be discovered.

The Electra and Burkburnett fields, a short distance west of Petrolia, produce only oil, which is derived from about the same horizon as the gas at Petrolia. Still farther west, in the central part of Wilbarger County, four wells drilled some years ago found small supplies of gas probably at a horizon somewhat above that of the productive sands at Petrolia. These wells are now exhausted, and no samples of the gas could be obtained.

On the Matthews ranch, in the southern part of Throckmorton County, five wells have been drilled, two of which found small volumes of gas at a depth of 1,050 feet. One of the wells was abandoned after two years of very moderate use, and the other had in July, 1918, an open flow of less than half a million cubic feet a day. Two samples of the gas tested for helium showed 0.22 and 0.73 per cent. The district was not visited by the writer, but in the opinion of the operator who drilled the wells there is little prospect of developing a commercial supply of the gas.

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[47] Shaw, E. W., Matson, G. C., and Wegemann, C. H., op. cit.

The Moran field, in the southeast corner of Shackelford County, contains about a dozen gas wells and a somewhat larger number of oil wells. One of the gas wells is 2,930 feet and another about 2,700 feet deep, but the others are approximately 2,000 feet deep. The open flow of the wells ranges between 3 million and 15 million cubic feet a day, and in July, 1918, the daily capacity of the field was perhaps 15 or 20 million cubic feet. Five samples of Moran gas were tested and found to contain from 0.27 to 0.41 per cent of helium. A pipe-line sample collected in January, 1918, contained 0.38 per cent, but a pipe-line sample collected in July showed only 0.27 per cent.

In the Ranger, Caddo, and Breckenridge fields, in Stephens and Eastland counties, oil and gas are produced chiefly from the Smithwick shale and Marble Falls limestone at depths of 3,000 to 3,500 feet, and this gas contains less than 0.1 per cent of helium. One well in the Breckenridge field, however, found gas in the Strawn formation at a depth of 2,230 feet and a sample of this gas carried 0.44 per cent of helium.

In the La Casa field, in Stephens County, and in the Strawn and Mineral Wells fields, in Palo Pinto County, large volumes of gas are produced from the Strawn formation. Two samples of gas from these fields showed only a trace of helium, and six others carried between 0.17 and 0.32 per cent, but the richer samples represent only a very small part of the supply. (See p. 106.)

Gas has been found in several wells near Bangs, in the western part of Brown County, and two samples of this gas contained 0.35 and 0.38 per cent of helium. A sample of gas from a well south of Coleman, in Coleman County, contained 0.22 per cent of helium, but the gas of the Trickham field, about 20 miles to the southwest, contains none.

APPALACHIAN REGION.

VINTON COUNTY FIELD, OHIO.

The field in Vinton County, Ohio, as at present developed centers in Richland Township (T. 9 N., R. 18 W.), but development is extending into the neighboring townships and the limits of the field are not yet defined. The field lies about 60 miles south of Columbus and about 3 miles west of the town of McArthur, on the Hocking Valley Railroad.

The main producing sand in the Vinton County field is in the Clinton sand, which is encountered at depths ranging between 1,700 and 2,400 feet. (See p. 102.) The accumulation of gas is not controlled by folding of the rocks but chiefly by the fact that the eastward-dipping Clinton sand feathers out and merges into shale in the western part of the county, the gas having apparently migrated up the dip and collected in the thinning edge of the sand. Similar conditions prevail along the strike of the rocks as far to the north as Cleveland,[a] and the sand is thus productive in many areas in a broad belt extending north and south in central Ohio. (See fig. 5.) The sand is somewhat variable in porosity and, of course, does not everywhere yield gas, but the Clinton fields, broadly considered, form an almost continuous belt of productive territory. The Vinton County pool lies at the southern extremity of the belt and is separated from the main fields by an area that has not yet proved productive, though a small pool has been discovered in the southern part of Hocking County, about 8 miles north of the main Vinton field. The gas in the Hocking County pool contains less helium than that in the Vinton field, and most of the Clinton gas north of Logan contains little nitrogen, and is presumably very poor in helium. It would therefore appear that the area in which the Clinton gas may be regarded as a source of helium does not extend far north of Hocking County; its southern limit, however, remains to be determined.

Drilling in the Vinton County area became active in 1915. In September, 1918, there were about 180 producing wells in the county, having an estimated potential production of 65 million cubic feet a day. As considerable areas that may be regarded as practically proved remain to be drilled, it is believed that the production could be increased to 100 million cubic feet a day and could be maintained at this figure for several years. The rock pressure of the wells in September, 1918, averaged about 700 pounds to the square inch.

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[a] Rogers, G. S., The Cleveland gas field, Cuyahoga County, Ohio: U. S. Geol. Survey Bull. 661, pp. 1-68, 1918.

Eighteen samples of Clinton gas from the Vinton County field showed an average helium content of 0.37 per cent, the extremes being 0.48 and 0.20 per cent. (See p. 102.) Two samples of gas from a sand near the horizon of the Berea, about 1,800 feet stratigraphically above the Clinton, contained 0.39 and 0.40 per cent, but the volume of this gas available is insignificant in comparison with that of the Clinton gas. Two samples of Clinton gas from the small pool in Hocking County contained 0.30 and 0.32 per cent of helium.

On the assumption that the Vinton County field is capable of producing 75 million cubic feet daily of gas carrying 0.37 per cent of helium, it is evident that the daily production of helium would be 277,500 cubic feet, which is more than twice as much as the Petrolia field is capable of producing. The utilization of the Vinton County gas as a commercial source of helium, however, depends entirely on conditions limiting the process of extraction. The results so far obtained in the experimental plants at Fort Worth indicate that the expense of treating a gas carrying only 0.37 per cent of helium, by either the Linde or the Claude process, would be prohibitive, but the Jeffries-Norton process offers promise of reducing the cost to a point at which such a gas could be profitably treated. If this can be done the large volume of gas available in Vinton County and its high pressure render the field very attractive as a source of helium.

ROCKY MOUNTAIN AND PACIFIC COAST REGIONS.

Gas containing about 0.3 per cent of helium has been found at three localities in the Rocky Mountain and Pacific coast regions, but the volumes available do not appear to be large. In view of the low helium content of the gas, the uncertainty as to the volume of the supply, and the location of the fields at considerable distances from manufacturing centers, these areas can not at present be regarded as commercial sources of helium. The main features of these fields have been described on pages 32–33.

AVAILABLE SUPPLY OF HELIUM IN THE UNITED STATES.

Gas fields are usually short lived in comparison with oil fields, but local conditions cause so much variation in the way in which gas wells are handled that it is impossible to formulate any rule as to the length of the productive period.

The maximum possible production of a gas well is its open flow—that is, the volume of gas that it is capable of delivering against atmospheric pressure—but if the well is allowed thus to flow open its yield diminishes very rapidly. In every field it is customary to maintain a definite pressure in the pipe line to which the well is attached and thus prevent the well from producing more than a part of its capacity. In some fields, however, the demand is such as to warrant taking 50 or 60 per cent of the open flow, whereas in others the production is held down to 20 or 25 per cent. By holding back the production the life of the field is of course lengthened and water troubles are more likely to be avoided, thus possibly increasing the total volume of gas ultimately recovered.

Because of this variation in operating conditions, no estimate of the available supply of helium that could be given here would have any permanent value; and furthermore, until processes of extraction are perfected it will be uncertain how lean a gas can be profitably treated. In September, 1918, the writer estimated that the Petrolia, Eldorado, Augusta, Dexter-Otto, and Sedan districts, all of which yield gas averaging more than 0.85 per cent of helium, were capable of producing a total of 363,800 cubic feet of helium daily for the next two and one-half to three years, provided some additional drilling were done and that the production were held down to 20 or 25 per cent of the open flow. Conditions have changed since the estimate was made, however, for during the winter of 1918–19 some of these fields produced considerably more than 20 to 25 per cent of their open-flow capacity, and the amount of gas remaining in the sands has been correspondingly decreased.

If gas containing as little as 0.5 per cent of helium can be profitably treated, the Pearson field and the neighboring territory will probably furnish a large supply, and it also appears probable that the western Osage country will yield gas carrying at least as much helium as that of the Pearson field. If gas containing as little as 0.37 per cent of helium can be treated, the Vinton County field is capable of furnishing at least a quarter of a million cubic feet of helium daily for several years. Taking into account every field producing at least 3 million cubic feet a day of raw gas containing at least 0.35 per cent of helium, the writer estimated in September, 1918, that a weekly production of about 6 million cubic feet of helium (not counting losses in extraction) could be maintained for two and one-half to three years.

As the extraction of helium in large quantities involves the installation of powerful compressors and other expensive machinery, it is obviously desirable to start operations in a field which is still young and in which the rock pressure is still high. Furthermore, it is desirable that the operations shall be aimed primarily at recovering the helium content of the gas and that the production be maintained, summer and winter, at a constant figure equal to the capacity of the extraction plant, thus prolonging the life of the field and extending the period of usefulness of the plant. Most of the helium-bearing fields of Kansas are now old and their product is in great demand as fuel, but the Pearson field, in Oklahoma, and the Vinton County field, in Ohio, are still comparatively young, and much of their product could be used as a source of helium without disturbing the local market. If new fields of helium-rich gas are discovered in the western Osage country or in northern Texas the operating conditions will of course be even more favorable.

POSSIBLE SOURCES OF HELIUM IN OTHER COUNTRIES.

As the conditions governing the occurrence of helium are very imperfectly known, it is impossible to forecast the importance of the supplies that may be developed in other countries. It may be of interest, however, to review the occurrences of helium abroad, as described in the literature, and to consider also the application to foreign fields of the principles that seem to govern the occurrence of helium in the United States.

So far as can be judged from the literature, no commercial supplies of helium-bearing natural gas have yet been discovered outside of North America. According to the writer's information, the richest gas in Canada is that of the Bow Island field, Alberta, which contains 0.30 per cent of helium and of which at the present time an open flow of about 15 million cubic feet is available. It is reported that attempts to extract the helium from the Bow Island gas have not been successful, though with an improvement in the extraction processes this gas may yet become a commercial source. Furthermore, considerable quantities of oil and gas are produced in other parts of Canada, where the conditions of occurrence are similar to those in the United States, and it is not unlikely that gas richer in helium than that of the Bow Island field will be discovered.

As described on pages 33–34 all but one of the European natural gases that have been tested contain negligible proportions of helium. The only gas rich enough to be considered a possible commercial source is the gas obtained from the deep test hole at Pechelbronn, Alsace, which contains 0.38 per cent of helium, but apparently only a very small volume of this gas is available.

It would of course be unwise to infer, from the results of half a dozen tests, that no helium-bearing natural gas occurs outside of North America, though several lines of reasoning lead to the conclusion that such gas is less likely to be found in the other continents. In the first place, the United States, which has contributed 60 per cent of the world's total output of oil, has furnished a very much larger proportion of the world's output of gas. This is doubtless due partly to the fact that most foreign petroleum regions are inaccessible and remote from centers of industrial activity, so that there is little market for the gas that may be found; but it seems safe to conclude, nevertheless, that natural gas is far more abundant in the United States than in any other country yet explored for petroleum. The only gas field in Europe comparable in size to the great North American fields is in Transylvania, and the several samples of gas from that field that have been tested contain practically no helium. As natural gas is more plentiful in the United States than elsewhere, it might be argued, simply on the theory of chances, that the helium-bearing variety is also more plentiful.

The conditions under which helium-bearing natural gas occurs in the United States also suggest that such gas is less likely to be found in other countries, though it must of course be recognized that these conditions may not prove to be of universal application. Except in the United States, Canada, and China, the world's output of oil and gas is at present derived wholly from Cretaceous and Tertiary strata, and in the United States the Cretaceous and Tertiary gases are characteristically poor in helium. Only about a dozen samples out of the seventy-five tested contained measurable proportions of helium, and only two contained as much as 0.3 per cent. The occurrence of 0.3 per cent in two samples indicates that there is no fundamental reason why helium should not occur in Cretaceous and Tertiary gases, but the large number of samples that contain no helium whatever suggest that such occurrences are rare. Finally, all helium-bearing natural gases in the United States are rich in nitrogen, whereas the many analyses of European gases that have been published show in general a low nitrogen content.[49] Only two accounts of high-nitrogen gas in Europe have come to the writer's attention—the deep gas at Pechelbronn, which contains 46.55 per cent of nitrogen and 0.38 per cent of helium (see p. 34), and a gas discovered in 1906 at Nowo-Usensk, in the Government of Samara, Russia. Two analyses of this gas showed 20.70 and 40.86 per cent of nitrogen, but the proportion of helium was undetermined.[50] Charitschkoff,[51] however, stated in 1907 that many of the Russian gases are rich in nitrogen and should be tested for helium, but that up to that time no search for helium had been made.

It is not to be inferred from the foregoing remarks that helium has not been found in quantity outside of North America, for as described on pages 47–51, the gases of a number of European mineral springs and fumaroles and the fire damp of some European mines carry helium. The gases of three mineral springs at Santenay, France, carry more than 8 per cent of helium, or more than four times as much as the richest natural gas in the United States. The supply of these gases available, however, is small, and the total volume of helium emitted by these three springs in the course of a year amounts to less than 1,000 cubic feet, or only a fraction as much as the average well in the Petrolia field yields daily. (See p. 87.) A spring at Néris, France, which emits gas containing 0.97 per cent of helium and produces about 1,200 cubic feet of helium yearly, appears to be the most productive single source of gas rich enough to be treated on a commercial scale. The mine gases, on the other hand, carry large volumes of helium, but the percentage is so small that the helium could not be profitably extracted. The coal mine at Anzin, France, for example, emits about 154,000 cubic feet of helium yearly, but the proportion of helium in the gas is only 0.044 per cent. (See p. 47.) The mineral springs and mine gases of Europe have been thoroughly investigated by Moureu and his associates, and it is improbable that any commercial sources of helium will be discovered among them.

The Italian fumarole and volcanic gases seem more likely to yield helium in commercial proportions and volume, though the richest gas recorded in the literature contains only 0.0155 per cent of helium. (See p. 51.) The helium content of many other similar gases was investigated during the war by the Italian authorities, and unsuccessful attempts were made to extract the helium on commercial scale for use in balloons. It has been reported, however, that gas containing 4 per cent of helium has recently been discovered in the boric-acid soffiones of Tuscany. As shown by the analyses on page 51, such gas generally consists chiefly of carbon dioxide and hydrogen sulphide, and as these constituents can easily be removed by chemical methods the extraction of only 1 per cent of helium from such a gas would not be difficult.

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[49] Engler has compiled a great many analyses of gas from various European countries. A number of these analyses show a high nitrogen content but also a high proportion of oxygen, indicating that the sample was contaminated by air. Engler, C., Das Erdöl, Band 1, pp. 738–744, Leipzig, 1913.

[50] The analyses also show 4.22 and 10.65 per cent of hydrogen and may therefore be regarded with some suspicion. Doss, B. Über das Naturgasbohrloch auf dem Gute der Gebrüder Melnikow im Kreise Nowo-Usensk, Gouvernement Samara [abstract]: Geol. Centralblatt, vol. 13, p. 8, 1909; Eine neue Lagerstätte von Naturgas in Russland [abstract]: Idem, p. 455; Über das dritte Gasbohrloch auf dem Gute der Gebrüder Melnikow im Gouvernement Samara nebst ergänzenden Untersuchungen über das zweite Bohrloch ebendaselbst: Idem, vol. 18, p. 55, 1912.

[51] Charitschkoff, K., Neue Mitteilungen über die Naphtachemie: Petroleum Zeitschr., vol. 2, p. 712, 1907.

SAMPLES OF NATURAL GAS TESTED FOR HELIUM.

The following list is designed as a complete catalogue of all samples of natural gas whose helium content had been determined prior to December 10, 1918. Samples collected in the field but lost through leaky containers or otherwise before tests were made are not included. The samples are grouped by States, counties, and fields, each in alphabetic order.

Most of the samples were collected by the writer and by members of the Geological Survey assisting him during the summer of 1918. Most of the samples from Wyoming, however, were collected during September, 1918, by C. A. Fisher, a former member of the Survey, and most of those from the Northwestern States and from California were collected by A. W. Ambrose and E. W. Wagy, of the Bureau of Mines, during August and September. Fairly complete data as to the name, location, depth, pressure, flow, and producing horizon of all wells sampled by Survey members and by Fisher, Ambrose, and Wagy are given in the tables. In order to make the catalogue as complete as possible the tests of a number of samples collected by C. F. Ward, of the Bureau of Mines, early in 1918, and by Cady and McFarland in 1906–7, are also included, despite the fact that all particulars regarding the source of many of these samples are not available.

The name of the collector of each sample is indicated by the letter prefixed to the sample number, as follows:

C 1–54, Cady and McFarland, 1906–7 (mostly Kansas).

W, C. F. Ward, 1917–18 (Oklahoma, Texas, Louisiana, California, etc.).

1–100, G. S. Rogers, June–September, 1918 (Kansas, Oklahoma, Texas).

Ry 1–101, P. V. Roundy, August–October, 1918 (Kansas).

D 1–13, C. E. Dobbin, August–September, 1918 (Oklahoma).

F 1–14, C. A. Fisher, September, 1918 (Wyoming).

A 1–70, A. W. Ambrose, August–September, 1918 (Northwestern States and California).

Ri 1–23, G. B. Richardson, August–September, 1918 (Ohio).

Samples C 1–54 were analyzed by Cady and McFarland at the University of Kansas; many of those marked W were tested by H. P. Cady or his assistants; and the remainder were tested by C. W. Seibel, of the Bureau of Mines, at the laboratory of the Fort Worth gas experiment plant.

In the tables the figures given for rock pressure and open flow are those recorded on the date the sample was collected unless otherwise specified.

Data on samples of natural gas

Indiana.

Sample No.	County.	Field.	Well.
			Name.
C 38	Grant	Marion	
		Kansas.	
C 26	Allen	Humboldt	Pipe-line sample
C 7	do.	Iola	do.
C 20	do.	Moran	
C 33	Anderson	Garnett	Pipe-line sample
W	Butler	Eldorado	Paulson well 47
W	do.	do.	Chesney well 3
W	do.	do.	Chesney (5 wells)
15	do.	do.	Wilson well 92
16	do.	do.	Stokes well 50
17	do.	do.	Lister well 24
18	do.	do.	Robinson well 37
18 A	do.	do.	McClure well 4
Ry 1	do.	do.	Stokes well 46
Ry 2	do.	do.	Stokes well 53
Ry 3	do.	do.	Pierpont well 36
Ry 4	do.	do.	Pierpont well 35
Ry 8	do.	do.	Chesney well 30
Ry 9	do.	do.	Wilson well 98
Ry 11	do.	do.	Robinson well 39
Ry 12	do.	do.	Robinson well 27
Ry 13	do.	do.	Howe well 25
Ry 16	do.	do.	Dickman well 10
Ry 18	do.	do.	Marsh well 25
Ry 19	do.	do.	Marsh well 28
Ry 20	do.	do.	Manning well 4
Ry 21	do.	do.	Enyart well 11
Ry 22	do.	do.	Anderson well 5
Ry 23	do.	do.	Anderson well 9
Ry 24	do.	do.	do.
Ry 25	do.	do.	Batman well 3
Ry 26	do.	do.	Batman well 2
Ry 27	do.	do.	Empire well 3
Ry 28	do.	do.	Nichelger well 1
Ry 29	do.	do.	Gussman well 1
Ry 30	do.	do.	Koogler well 1
Ry 31	do.	do.	Empire well 8
Ry 32	do.	do.	John Boyer well 11
C 37	do.	Augusta	Pine-line sample
W	do.	do.	
20	do.	do.	Moyle well 7
21	do.	do.	Love well 1
19	do.	do.	Wallace well 1
22	do.	do.	Pipe-line sample 21 wells
Ry 38	do.	do.	E. Varner well 2
Ry 39	do.	do.	E. Varner well 15
Ry 40	do.	do.	do.
Ry 41	do.	do.	Haskins well 6
Ry 42	do.	do.	Haskins well 1
Ry 43	do.	do.	Love well 19
Ry 44	do.	do.	Skaer well 1
Ry 45	do.	do.	Starkey well 5
Ry 46	do.	do.	Moyle well 2
Ry 48	do.	do.	Miller well 3
Ry 49	do.	do.	Collins well 1
Ry 51	do.	do.	Scully well 1
Ry 52	do.	do.	Penley well 1
Ry 53	do.	do.	Cunningham well 2
Ry 54	do.	do.	E. Varner well 1
Ry 55	do.	do.	Smith well 1
Ry 56	do.	do.	Ralston well 1
Ry 57	do.	do.	Brown well 1

[a] Line pressure. [b] Average depth of wells. [c] May, 1918. [d] Shawnee formation.

tested for helium—Continued.

Indiana.

Well—Continued.					Producing sand.		Date sampled.	Helium (per cent).
Locality.			Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet).		
Section.	Township.	Range.						
					Ordovician (Trenton ?).		Aug. 25, 1906	0.167

Kansas.

					Pennsylvanian		July 25, 1906	0.14
					do.		June 10, 1906	.18
					do.		July 13, 1906	.21
			200		do.	[b] 600	Aug. 1, 1906	.37
2	26 S.	4 E.	[a] 100	[c] 450	do.[d]	895- 920	1918	1.59
21	25 S.	5 E.	[c] 84	[c] 700	do.[e]	1,248	1918	.79
21	25 S.	5 E.	[c] Av., 72		do.[e]	1,218-1,236	1918	1.04
8	25 S.	5 E.	[c] 348	[c] 3,075	do.[e]	1,270-1,292	July 15, 1918	.587
33	25 S.	5 E.	[c] 43	[c] 250	do.[d]	854- 860	do.	1.008
32	25 S.	5 E.	[c] 310	[c] 600	do.[e]	1,176-1,185	do.	1.162
31	25 S.	5 E.	[c] 82	[c] 325	do.[d]	900- 905	do.	1.568
14	26 S.	4 E.			do.[d]	About 900	do.	1.41
33	25 S.	5 E.	[c] 38	[c] 275	do.[e]	1,093-1,110	Aug. 19, 1918	1.36
33	25 S.	5 E.	[c] 37	[c] 200	do.[f]	865- 875	do.	.72
33	25 S.	5 E.	[c] 42	[c] 225	do.[f]	880- 892	do.	1.42
33	25 S.	5 E.	[c] 43	[c] 115	do.[f]	842- 850	do.	1.36
21	25 S.	5 E.	[c] 270	[c] 375	do.[e]	1,255-1,261	Aug. 20, 1918	1.18
8	25 S.	5 E.		[c] 650	do.[e]	1,295-1,302	do.	1.70
31	25 S.	5 E.	[c] 90	[c] 350	do.[f]	894- 901	do.	1.19
31	25 S.	5 E.	[c] 146	[c] 504	do.[e]	1,273-1,315	do.	.75
5	26 S.	5 E.	[c] 170	[c] 375	do.[e]	1,250	do.	.71
36	25 S.	4 E.	[c] 76	[c] 350	do.[f]	897- 909	Aug. 27, 1918	1.22
6	26 S.	5 E.	[c] 104	[c] 275	do.[e]	1,270-1,280	do.	.48
6	26 S.	5 E.	[c] 122	[c] 105	do.[e]	1,136-1,272	do.	.93
5	26 S.	5 E.	[c] 252	[c] 130	do.[e]	1,129-1,210	do.	1.39
12	26 S.	4 E.	[c] 252	[c] 275	do.[e]	1,170-1,190	do.	1.26
8	26 S.	5 E.	[c] 48	[c] 35	do.[f]	901- 912	do.	1.21
7	26 S.	5 E.	[c] 42	[c] 265	do.[f]	910- 918	do.	1.10
8	26 S.	5 E.	[c] 50	[c] 425	do.[f]	900- 905	do.	1.13
8	26 S.	5 E.	[c] 46	[c] 280	do.[f]	904- 914	do.	1.16
8	26 S.	5 E.	[c] 48	[c] 375	do.[f]	892- 898	do.	1.07
17	26 S.	5 E.	[c] 66	[c] 265	do.[f]	887- 899	do.	1.11
17	26 S.	5 E.	[c] 214	[c] 200	do.[f]	875- 887	do.	.91
17	26 S.	5 E.	[c] 50	[c] 160	do.[f]	885- 892	do.	1.24
17	26 S.	5 E.	[c] 56	[c] 210	do.[f]	840	do.	1.17
17	26 S.	5 E.	[c] 238	[c] 325	do.[f]	864-1,082	do.	1.19
8	26 S.	5 E.		[c] 190	do.[f]	1,110-1,185	do.	1.20
			650		do.[f]	1,440	Aug. 4, 1906	.25
			75±		do.	About 500	1918	1.94
35	27 S.	4 E.	[g] 75±	[g] 400	do.	About 550	July 18, 1918	2.13
20	28 S.	4 E.	[g] 350	[g] 4,500	do.	1,434-1,442	do.	.414
11	28 S.	4 E.	[g] 120	[g] 205	do.	1,455-1,542	do.	.55
([h])	([h])	([h])			do.		do.	.518
8	28 S.	4 E.	[g] 124	[g] 294	do.	1,190-1,220	Sept. 2, 1918	.16
17	28 S.	4 E.	[g] 108	[g] 213	do.	1,611	do.	.31
17	28 S.	4 E.	[g] 250	[g] 25	do.	1,395	do.	.38
17	28 S.	4 E.	[g] 76	[g] 823	do.	1,350	do.	.21
17	28 S.	4 E.	[g] 163	[g] 94	do.	1,420	do.	.38
29	28 S.	4 E.	[g] 241	[g] 1,700	do.	1,419	do.	.62
26	27 S.	4 E.	[g] 190	[g] 251	do.	1,395	Sept. 3, 1918	.55
35	27 S.	4 E.			do.	1,520	do.	.65
35	27 S.	4 E.			do.		do.	.48
2	28 S.	4 E.	[g] 66	[g] 115	do.	1,428-1,500	do.	.42
2	28 S.	4 E.	[g] 163	[g] 115	do.	1,452	do.	.57
21	27 S.	4 E.	[g] 167	[g] 190	do.	1,350-1,442	Sept. 7, 1918	1.03
21	27 S.	4 E.	[g] 162	[g] 190	do.	1,320	do.	1.14
15	28 S.	4 E.	[g] 58	[g] 48	do.	1,425-1,485	do.	.42
16	28 S.	4 E.	[g] 133	[g] 167	do.	1,378-1,418	do.	.40
20	28 S.	4 E.	[g] 195	[g] 305	do.	1,367-1,427	do.	.40
8	28 S.	4 E.	[g] 94	[g] 167	do.	1,358-1,452	do.	.44
16	28 S.	4 E.	[g] 206	[g] 94	do.	1,390-1,473	do.	.41

[e] Douglas or Lansing formation.

[f] Shawnee formation.

[g] July, 1918.

[h] Chiefly in secs. 2, 3, 10, and 11, T. 28 S., R. 4 E.

Data on samples of natural gas

Kansas—Continued.

Sample No.	County.	Field.	Well.
			Name.
Ry 59	Butler	Augusta	Feltham well 3
Ry 60	do	do	Hazlett well 2
C 40	Chase	Elmdale	
Ry 35	do	do	O'Neil well 1
Ry 36	do	do	C. M. Breese well 1
W	Chautauqua	Sedan (Rogers pool)	Pipe line at compressor station
25	do	do	do
Ry 95	do	do	do
26	do	Sedan	Roth well 1
Ry 81	do	Sedan (Rogers pool)	Holroyd well 5
Ry 82	do	do	Gray well 2
Ry 87	do	do	Hopkins well 2
Ry 88	do	do	Hopkins well 3
Ry 89	do	do	Hopkins well 6
Ry 90	do	do	Hopkins well 4
Ry 91	do	do	Long well 2
Ry 93	do	do	F. E. Smith well 2
Ry 94	do	do	Butcher well 1
Ry 96	do	do	Butcher well 2
Ry 97	do	do	Barr well 1
Ry 98	do	do	Call well 1
Ry 100	do	do	Butcher well 1
89	do	Sedan	Stevens & Graham well 1
102	do	do	Abandoned well
28	do	do	Fleming & Wadsworth well
93	do	do	White & Toews well
92	do	do	Wall well
91	do	do	Brant well 2
Ry 101	do	do	T. Smith well 1
W	do	do	Gregg well
94	do	Chautauqua	Pipe-line sample
95	do	do	Williams well 1
86	do	Hale	Ferguson well 2
87	do	do	Brand well 1
88	do	Havana	Pipe-line sample
97	do	Monett	Lamb well
C 23	do	Peru	
C 36	Coffey	Burlington	Pipe-line sample
C 17	Cowley	Arkansas City	
C 1	do	Dexter	Discovery well
C 6	do	do	Greenwell well
W	do	do	
77	do	do	Hale well
78	do	do	Bolton well
W	do	Otto	Phillips well
W	do	do	Standish well 2
79	do	do	Day well 1
80	do	do	Melick gas well
24	do	Winfield	Pipe-line sample
C 4	Douglas	Eudora	do
C 11	do	Lawrence	Old well
84	Elk	Longton	Ruddle well 4
85	do	do	Ruddle well 1
C 8	do	Moline	Pipe-line sample
C 27	do	New Albany	
81	do	Oak Valley	Simmons well 2
82	do	do	Gardner well 5
Ry 15	Greenwood	Beaumont	G. R. Lewis well 1
C 41	do	Eureka	Pipe-line sample
Ry 14	do	do	John Edwards well
Ry 34	do	Toronto	West Virginia Oil & Gas Co. well 1
Ry 33	do	Virgil	Foster Oil Co. well 2
C 34	Johnson	Spring Hill	Pipe-line sample
W	Labette		Carroll well 1
W	do		King well 1
W	do		Wilson well 1
C 15	Leavenworth	Bonner Springs	Pipe-line sample

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[a] July, 1918.
[b] Small.
[c] Kansas City formation.
[d] Approximate.
[e] Casing-head gas.
[f] Peru sand.

tested for helium—Continued.

Kansas—Continued.

Well—Continued.					Producing sand.		Date sampled.	Helium (per cent).
Locality.			Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet).		
Section.	Township.	Range.						
10	28 S.	4 E.	[a]133	[a]215	Pennsylvanian		Sept. 7, 1918	0.47
11	28 S.	4 E.	[a]111	[a]94	do	1,755	do	.46
			45	1,000	do	150	Oct. 6, 1906	.56
1	20 S.	7 E.	34	([b])	do	340	Aug. 31, 1918	.35
34	19 S.	7 E.	36		do	580	do	.50
					do		Apr. —, 1918	.89
					do		July 18, 1918	1.009
					do		Sept. 25, 1918	.98
34	33 S.	10 E.	100	500	do.[c]	[d]700	July 18, 1918	1.912
24	33 S.	10 E.	40	685	do.[c]	[d]754	Sept. 22, 1918	.59
24	33 S.	10 E.	24		do.[c]	[d]661	do	.99
35	33 S.	10 E.	12		do.[c]	[d]575	do	.86
35	33 S.	10 E.	27	500	do.[c]	[d]619	do	1.14
35	33 S.	10 E.	25		do.[c]	[d]606	do	1.16
35	33 S.	10 E.	30	116	do.[c]	[d]883	Sept. 24, 1918	1.07
30	33 S.	10 E.	40	395	do.[c]	[d]712	do	.97
25	33 S.	10 E.	36	184	do.[c]	[d]700	do	.93
25	33 S.	10 E.	40	395	do.[c]	[d]700	do	1.05
25	33 S.	10 E.	36	479	do.[c]	[d]700	do	1.03
36	33 S.	10 E.	36	213	do.[c]	[d]735	Sept. 25, 1918	.94
36	33 S.	10 E.	45	282	do	[d]728	do	.98
36	33 S.	10 E.	43	480	do	[d]870	do	.90
14	34 S.	10 E.	([e])	1,000	do	[f]1,400	Sept. 15, 1918	.41
28	33 S.	11 E.			do	(?)	Oct. —, 1918	.72
27	33 S.	11 E.	50	500	do	375	July 18, 1918	1.94
26	33 S.	11 E.	5	10	do	400	Sept. 15, 1918	1.04
29	33 S.	11 E.	100	500	do	700	do	.84
16	33 S.	11 E.	[g]300		do	900	do	.80
17	33 S.	11 E.	1	50	do	896	Oct. 10, 1918	.89
21	33 S.	11 E.			do	700±	1918	.70
16	35 S.	11 E.	[h]70	500	do	[i]800	Sept. 16, 1918	.21
16	35 S.	11 E.	130	500	do	600	do	.43
31	32 S.	13 E.	68	1,000	do	300	Sept. 17, 1918	.35
31	32 S.	13 E.	80	500	do	640	do	.36
	34 S.	13 E.	[h]37	[j]4,000	do	[i]800	do	.37
33	33 S.	12 E.	35	250	do	[k]550	Sept. 18, 1918	.57
					do		1906	.19
					do		Aug. 4, 1906	.49
			355	5,000	do	750	1906	.16
18	33 S.	7 E.	110	6,000	do	310	1905	1.84
18	33 S.	7 E.	110	4,000	do	310	June 12, 1906	1.64
18	33 S.	7 E.			do	700	1918	.955
13	33 S.	6 E.	10	5	do	350	Aug. 31, 1918	1.83
13	33 S.	6 E.	10	5	do	350	do	1.68
17	35 S.	7 E.	420	2,500	do	1,475	Mar. 18, 1918	1.047
17	35 S.	7 E.	495	3,850	do	1,475	Mar. 4, 1918	.94
24	34 S.	6 E.	250	1,500	do	1,145	Aug. 31, 1918	1.90
13	34 S.	6 E.	15	10	do	1,150	do	.50
				[l]500	do		July 17, 1918	.38
5	13 S.	21 E.	[h]200		do	[i]350	1906	.27
					do	1,200	July 4, 1906	.46
31	31 S.	12 E.	210	1,360	do	758	Sept. 3, 1918	.55
31	31 S.	12 E.	135		do	514	do	.54
			[h]380		do	[i]1,150	June 24, 1906	.51
					do		July 25, 1906	.49
27	31 S.	13 E.	550	30,000	do	1,340	Sept. 3, 1918	.001
20	31 S.	13 E.	[g]210	1,500	do	505	do	.40
25	27 S.	8 E.	250±	1,600	do	1,120	Aug. 29, 1918	.86
			[h]85		do	[i]375	Oct. 25, 1906	1.50
3	26 S.	10 E.	10	10	do	450	Aug. 22, 1918	1.42
16	26 S.	13 E.		1,000	do	1,415	Aug. 30, 1918	.36
23	24 S.	12 E.	70	2,000	do	500	do	.65
			[m]184		do	[i]580	Aug. 2, 1906	.40
					do		1918	.05
					do		1918	.06
					do		1918	.05
			[m]190		do	[i]600	July 8, 1906	.10

[g] Initial pressure.

[h] Line pressure.

[i] Average depth of wells

[j] Combined flow of about 35 wells.

[k] Salt sand

[l] Production of field.

[m] Average rock pressure of wells.

Data on samples of natural gas

Kansas—Continued.

Sample No.	County.	Field.	Well.
			Name.
C 22	Montgomery	Caney	Caney Gas & Min. Co.
C 18	do	Coffeyville and Liberty	Pipe-line sample
C 45	Neosho	Several fields	do
C 25	do	Chanute	do
C 12	do	Erie	do
C 28	Wilson	Altoona	
C 31	do	Buffalo	
C 9	do	Fredonia	Pipe-line sample
C 10	do	Neodesha	
C 16	do	do	Pipe-line sample
		Louisiana.	
W	Bossier	Bossier	Reserve Gas Co. well
W	Caddo	Cedar Grove	Southwestern Gas Co. well
C 46	Jefferson Davis	Jennings	Oil well
W	Ouachita	Munroe	Smith well 1
W	do	do	Smith well 2
W	Terrebonne	Houma	McCormick well 2
W	do	do	H. J. Gidry well
		Missouri.	
C 43	Jackson		Well at 2416 Tracy Avenue, Kansas City
C 44	do	Sheffield	
		Montana.	
A 2	Dawson	Glendive	Sample from four wells
A 1	Fallon	Baker	Sample from three wells
A 5	Hill	Havre	Brewery well
		North Dakota.	
A 3	Ward	Minot	
		Ohio.	
Ri 10	Hocking	Vinton	W. A. Williamson well
Ri 11	do	do	Mahlon Paxton well
C 24	Richland	Butler	F. O. Levering well
W	Vinton	Vinton	Pipe-line sample
Ri 0	do	do	do
Ri 1	do	do	Ohio Fuel Supply Co. well 1592
Ri 2	do	do	Ohio Fuel Supply Co. well 1737
Ri 3	do	do	Ohio Fuel Supply Co. well 1919
Ri 4	do	do	Ohio Fuel Supply Co. well 2109
Ri 5	do	do	Ohio Fuel Supply Co. well 1634
Ri 6	do	do	Pipe-line sample
Ri 7	do	do	do
Ri 8	do	do	Oil Fuel Supply Co. well 2364
Ri 9	do	do	Oil Fuel Supply Co. well 2140
Ri 15	do	do	Oil Fuel Supply Co. well 2281
Ri 16	do	do	Ohio Fuel Supply Co. well 1991
Ri 18	do	do	Ohio Fuel Supply Co. well 2224
Ri 19	do	do	Ohio Fuel Supply Co. well 1779
Ri 20	do	do	Ohio Fuel Supply Co. well 1788
Ri 21	do	do	Ohio Fuel Supply Co. well 634
Ri 22	do	do	Ohio Fuel Supply Co. well 2727
Ri 23	do	do	Ohio Fuel Supply Co. well 2062
W	Washington	Vincent	W. H. Bell well

[a] Average rock pressure of wells.

[b] Average depth of wells.

[c] Depth of wells.

[d] Average of wells sampled.

tested for helium—Continued.

Kansas—Continued.

Well—Continued.					Producing sand.		Date sampled.	Helium (per cent).
Locality.			Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet).		
Section.	Township.	Range.						
	35 S.	13 E.	620		Pennsylvanian	1,550	July 14, 1906	0.08
					do		1906	.08
					do		Dec. 12, 1906	.17
			[a] 200		do	[b] 850	July 24, 1906	.24
			[a] 150		do	[b] 150	July 3, 1906	.13
					do		July 25, 1906	.26
7	27 S.	16 E.			do		July 28, 1906	.27
			300–480		do	[c] 1,085–1,250	1906	.62
							June 27, 1906	.10
							1906	.27

Louisiana.

Section.	Township.	Range.	Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet).	Date sampled.	Helium (per cent).
			350	Large.	Cretaceous	800– 900	1918	.028
					do		1918	.046
			1		Tertiary		Feb. —, 1907	Trace.
					Cretaceous		1918	.053
					do		1918	.075
					Tertiary		1918	Trace.
					do		1918	Trace.

Missouri.

Section.	Township.	Range.	Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet).	Date sampled.	Helium (per cent).
				0.5	Pennsylvanian	300	1906	.013
			40	1.6	do	Shallow.	1906	.041

Montana.

Section.	Township.	Range.	Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet).	Date sampled.	Helium (per cent).
			[d] 12	[e] 250	Cretaceous	768–800	Aug. 13, 1918	.05
			[d] 65	[e] 1,500	do	835–890	Aug. 12, 1918	.005
			475	50	do	1,200	Aug. 16, 1918	.27

North Dakota.

Section.	Township.	Range.	Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet).	Date sampled.	Helium (per cent).
			5	35	Cretaceous	357	Aug. 15, 1918	.17

Ohio.

Section.	Township.	Range.	Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet).	Date sampled.	Helium (per cent).
	11 N.	19 W.	[f] 510	[g] 230	Silurian[h]		Aug. —, 1918	.32
	11 N.	19 W.	[f] 675	[g] 3,120	do.[h]		do	.30
			1,200		do.[h]		July 19, 1906	.15
							1918	.491
3	9 N.	18 W.					Aug. 12, 1918	.28
34	10 N.	18 W.					do	.34
28	10 N.	18 W.	[f] 605	[g] 2,400	Silurian.[h]	2,296	do	.36
23	10 N.	18 W.	[f] 530	[g] 1,300	do.[h]	2,430	do	.39
6	11 N.	17 W.	[f] 820	[g] 2,059	do.[h]	2,560	do	.38
18	9 N.	18 W.	[f] 900	[g] 4,250	do.[h]	2,072	do	.39
15	9 N.	18 W.			do.[h]		Aug. 13, 1918	.38
22	9 N.	18 W.			do.[h]		do	.27
3	8 N.	18 W.	[f] 135	[g] 160	Mississippian [i]	849	do	.39
34	9 N.	18 W.	[f] 860	[g] 8,853	Silurian [h]	2,346	do	.48
1	9 N.	18 W.	[f] 875	[g] 5,000	do.[h]	2,653	Sept. —, 1918	.44
10	9 N.	18 W.	[f] 790	[g] 213	do.[h]	2,498	do	.43
19	9 N.	18 W.	[f] 550	[g] 9,510	do.[h]	2,155	do	.44
16	9 N.	18 W.	[f] 810	[g] 421	do.[h]	2,366	do	.20
26	9 N.	18 W.	[f] 840	[g] 519	do.[h]	2,478	do	.40
1	8 N.	18 W.	[f] 240		Mississippian [i]	660	do	.40
3	8 N.	18 W.	[f] 675	[g] 421	Silurian [h]	2,438	do	.38
33	9 N.	18 W.	[f] 825	[g] 4,300	do	2,321	do	.34
							1918	.17

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[e] Combined flow of wells sampled. [f] Initial pressure. [g] Initial open flow. [h] Clinton sand. [i] Probably Berea sand.

Data on samples of natural gas

Oklahoma.

Sample No.	County.	Field.	Well.
			Name.
W	Caddo	Cement	Gregory well 1
11	Carter	Fox	Mattie Morris well 2
12	do	do	Lucinda well 1
W	Cotton	Keyes	J. C. Keyes well 1
W	do	do	Pipe-line sample
W	Creek	Bristow	Shields well 1
C 32	Kay	Blackwell	Union Gas & Oil Co. well 2
D 6	do	do	Hennessey well 1
D 7	do	do	Ira Shutz well 2
D 8	do	do	Ira Shutz well 5
D 9	do	do	Hobaugh well 2
D 10	do	do	Dilworth well 1
D 11	do	do	Kay & Kiowa Oil Co. well
D 12	do	Ponca City	J. D. Buntt well 1
D 13	do	do	Margaret Primaux well 7
D 1	Noble	Billings	E. N. Gillespie well 1
D 5	do	do	Iva B. Read well 1
99	Osage	Osage City	Braden & Moore well 1
100	do	do	Braden & Moore well 8
36	do	Pawhuska	Indian Territory Illuminating Oil Co. well 208.
W	do	Myers	
29	do	do	American Pipe Line Co. well 18
30	do	do	American Pipe Line Co. well 7
31	do	do	Pipe-line sample (5 wells)
W	do	Pearson	American Pipe Line Co. well 4
W	do	do	American Pipe Line Co. well 2
W	do	do	American Pipe Line Co. well 3
W	do	do	American Pipe Line Co. well 1
W	do	do	American Pipe Line Co. well 2
W	do	do	
W	do	do	Pipe-line sample, all wells
W	do	do	do
32	do	do	American Pipe Line Co. well 29
33	do	do	American Pipe Line Co. well 28
34	do	do	American Pipe Line Co. well 53
35	do	do	Pipe-line sample, all wells
W	Pawnee	Morrison	Fortuna well 1
W	do	do	G. L. Miller well 1
W	do	do	D. Miller well
W	do	do	Saunders well 17
W	Payne	Ingalls	Chevalier well
W	do	do	do
14	Pontotoc	Ada	Pipe-line sample
W	Stephens	Duncan	Washita Gas & Fuel Co. well
W	do	Loco	Allen & Gilbert well 3
W	do	do	Allen & Gilbert well 2
W	do	do	Mullen & Robinson well 1
C 14	Washington	Bartlesville	

South Dakota.

C 54	Hughes	Pierre	

[a] Initial rock pressure. [b] Bruner sand. [c] Initial open flow. [d] Casing-head gas. [e] Average depth of wells.

tested for helium—Continued.

Oklahoma.

Well—Continued.					Producing sand.		Date sampled.	Helium (per cent).
Locality.			Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet).		
Section.	Township.	Range.						
31	6 N.	9 W.		35,000	Pennsylvanian	2,340	Sept. —, 1918	0.089
28	2 S.	3 W.	540	40,000	do	1,950	June 30, 1918	Trace.
29	2 S.	3 W.	280	30,000	do	1,450	do	.06
23	1 S.	10 W.	[a] 900	9,500	do	2,178	1918	.097
	1 S.	10 W.			do		1918	.06
30	15 N.	9 E.	310	744	do.[b]	965	Mar. 22, 1918	.15
			185	1,000	Permian	640	July 31, 1906	.16
30	29 N.	1 E.	125	280	do	700	Aug. 30, 1918	.20
31	29 N.	1 E.	550	7,250	Pennsylvanian	2,186	do	.17
31	29 N.	1 E.	280	4,600	do	1,370	do	.14
30	29 N.	1 E.	500	9,000	do	1,868	Aug. 29, 1918	.22
5	28 N.	1 E.	150	800	Pennsylvanian?	930	do	.17
13	28 N.	1 W.	170	1,000	Permian	787	do	.27
18	25 N.	2 E.	14	450	Pennsylvanian	610	Sept. 2, 1918	.37
4	25 N.	2 E.	21	500	do	440	do	.36
21	23 N.	2 W.	85	[c] 10,000	do	1,052	Aug. 28, 1918	.39
29	24 N.	1 W.	60	250	Permian	574	do	.10
12	21 N.	8 E.	([d])		Pennsylvanian	600	Sept. 1, 1918	.003
12	21 N.	8 E.	([d])		do	600	do	.15
36	26 N.	9 E.			do	1,988	July 18, 1918	.06
12	26 N.	8 F.			do		1918	.43
12	26 N.	8 E.	50	1,000	do	549	July 18, 1918	.35
12	26 N.	8 E.	340	1,250	do	1,122	do	.27
					do	[e] 1,100	do	.37
					do		Feb. —, 1918	.71
					do		Feb. 9, 1918	.65
					do		Feb. —, 1918	.62
					do		do	.58
					do		Feb. 14, 1918	.62
					do	1,200	Feb. —, 1918	.48
					do		do	.53
					do		do	.55
20	27 N.	8 E.	100	1,000	do	918	July 18, 1918	.23
19	27 N.	8 E.	98	1,020	do	790	do	.54
22	27 N.	8 E.	500	2,000	do	1,442	do	.33
					do		do	.48
	23 N.	3 E.			do		1918	.24
	23 N.	3 E.		[c] 40,000	do	2,040		.22
	23 N.	3 E.			do			.27
	23 N.	3 E.			do			.22
27	19 N.	4 E.			do		Nov. 14, 1917	.35
27	19 N.	4 E.			do	([f])	Jan. 24, 1918	.05
	24 N.	6 E.	[g] 440	[h] 100,000	do	[e] 1,100	June 30, 1918	.05
12	1 N.	6 W.			Permian	850	1918	Trace.
	3 S.	5 W.			do		1918	.18
	3 S.	5 W.			do		1918	.17
	3 S.	5 W.			do		1918	.16
					Pennsylvanian		July 8, 1906	Present.

South Dakota.

Section.	Township.	Range.	Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet).	Date sampled.	Helium (per cent).
					Cretaceous		1906	Trace.

[f] Below 1,800 feet.

[g] Initial average rock pressure of field.

[h] Capacity of field.

Data on samples of natural gas

Texas.

Sample No.	County.	Field.	Well.
			Name.
69	Brown	Bangs	Fuller well
71	do	do	McGee well
C	Clay	Petrolia	Pipe-line sample
C	do	do	do
	do	do	Pipe-line sample [c]
1	do	do	Miller well 4
2	do	do	Smith & Weber well 1
3	do	do	Holloway well 7
4	do	do	Landrum well 2
5	do	do	Holt well 1
6	do	do	Byers well 5
7	do	do	Stive Oil & Gas Co. well 1
8	do	do	H. D. Stive well
9	do	do	Skelly well
10	do	do	Martin well 5
W	Coleman	Trickham	Robinson well 2
68	do	Coleman	Wood & Wooley well 1
46	Eastland	Ranger	Brashear well 1
W	Limestone	Mexia-Groesbeck	4 samples from different wells
47	Palo Pinto	Mineral Wells	G. W. Dye well 1
48	do	do	Holt well 1
49	do	do	Frank Corn well 1
50	do	do	Jacques well 1
54	do	do	J. E. Hess well 2
55	do	do	D. A. Hess well 1
56	do	do	J. E. Hess well 1
57	do	do	Edmundson well 1
60	do	do	Gill well 1
38	do	Strawn	Pierce well 2
40	do	do	Robinson well 2
41	do	do	Unkhart well 271
42	do	do	Pipe-line sample
72	do	do	Stewart well 75
61	Shackelford	Moran	Formby-Tarrant well 1
62	do	do	Pipe-line sample (all wells)
65	do	do	Edwards well 1
66	do	do	Cottle well 1
67	do	do	Pipe line, 11 wells
	Stephens	Strawn	See Palo Pinto County
43	do	Caddo	Coody well 1
39	do	La Casa	Rainey well 1
73	do	do	Adams well 1
W	do	Breckenridge	Smith well 1
W	Throckmorton	Matthews	Texas Co. well 4
W	do	do	Texas Co. well [m]
W	Zapata	Jennings	
W	Williamson	Thrall	Magnolia Oil Co

Washington.

A 9	Benton	Prosser	

---

[a] Strawn formation.
[b] Cisco formation.
[c] Analysis by Moore and Yancey, Bureau of Mines Experiment Station, Golden, Colo.
[d] June 1, 1918.
[e] January 1, 1918.
[f] Initial open flow.
[g] Lower part of Canyon formation or upper part of Strawn formation.
[h] Contact between Marble Falls limestone and Smithwick shale.

tested for helium—Continued.

Texas.

Well—Continued.			Producing sand.		Date sampled.	Helium (per cent).
Locality.	Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet).		
Near Bangs	430		Pennsylvanian [a]	1,190	July 27, 1918	0.35
7 miles south of Bangs			do	1,500±	1918	.38
			Pennsylvanian [b]		Dec. 11, 1917	.985
			do		June 13, 1917	.88
					Oct. 30, 1917	.966
Sec. 59, school land			Pennsylvanian [b]	1,543–1,599	June 28, 1918	.71
Sec. 37, school land	[d] 75	[e] 192	do. [b]	1,576–1,583	do	1.15
Sec. 29, school land	[d] 120		do. [b]	1,704–1,718	do	.65
Sec. 5, school land	[d] 90	[e] 3,157	do. [b]	1,761	do	.76
Sec. 15, school land	[d] 75	[e] 67	do. [b]	1,564–1,571	do	.96
Sec. 14, Byers Bros. survey	[d] 25	[e] 676	do. [b]	1,568–1,621	do	1.00
Sec. 1, school land	[d] 25	[e] 852.48	do. [b]	1,694–1,731	do	.88
Sec. 34, school land	[d] 185	[e] 962.88	do. [b]	1,810	do	1.11
Sec. 36, school land	[d] 80	[e] 1,989.12	do. [b]	1,602–1,620	do	.88
2 miles west of Petrolia	650	[f] 6,000	do. [b]	1,671–1,683	do	1.18
			do. [g]		1918	None.
7 miles southwest of Coleman		25,000	do. [g]		July 27, 1918	0.22
5 miles south of Ranger		[f] 6,000	do. [h]	3,035	July 25, 1918	.08
			Upper Cretaceous [i]		1918	Trace.
1 mile southeast of Graford			Pennsylvanian [a]	2,951	July 16, 1918	[j] 0.2
11 miles north of Palo Pinto			do. [a]	1,270	do	.3 [j] 5.0
4 miles east of Palo Pinto			do. [a]	2,200	do	[j] 3.0
1½ miles south of Mineral Wells.			do. [a]	1,004	do	[j] 3.0
5½ miles south of Mineral Wells.		10,000	do. [a]	1,052	July 17, 1918	[j] 3.0
6 miles south of Mineral Wells		11,000	do. [a]	1,045	do	[j] 3.0
do		2,000	do. [a]	1,035	do	[j] 2.0
7 miles south of Mineral Wells			do. [a]	1,150	July 18, 1918	[j] 3.0
5 miles south of Mineral Wells			do. [a]	997	Jan. —, 1918	.17
Sec. 82, block 4, Texas & Pacific Coal Co.'s survey.			do. [a]	1,830	July 19, 1918	.18
Sec. 78, block 4, Texas & Pacific Coal Co.'s survey.	500		do	1,508	do	.32
2 miles west of Strawn	110		do. [a]	675	do	[j] 10.0
Thurber, Erath County			do. [a]	600–900	do	.19
Sec. 95, block 4, Texas & Pacific Coal Co.'s survey.			do. [a]	1,000±	Jan. —, 1918	.17
			do. [a]	2,930	do	.31
			do. [a]	[k] 2,000	do	.38
		3,000	do. [a]	2,000	July 24, 1918	.39
		4,000	do. [a]	2,700	do	.41
			do. [a]	[k] 2,000	do	.27
Sec. 41, block 4, Texas & Pacific Coal Co.'s survey.			Pennsylvanian	3,298	July 21, 1918	.07
Sec. 45, block 6, Texas & Pacific Coal Co.'s survey.		35,000	do. [a]	1,985	do	Trace.
Sec. 65, block 6, Texas & Pacific Coal Co.'s survey.		Large.	do. [a]	2,134	do	Trace.
5 miles south of Breckenridge		16,000	do. [a]	2,230	June —, 1918	.44
Lambshead ranch	200	400	do. [l]	1,050	1918	.22
do			do	1,050	1918	.73
Jennings ranch	300	10,000	Tertiary [n]	1,250	1918	.006
			Cretaceous [o]		1918	None.

Washington.

	5	4,500	Tertiary [p]	730	Aug. 19, 1918	0.06

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[i] Nacatoch sand member of Navarro formation.
[j] Nitrogen.
[k] Average depth of wells.
[l] Possibly Cisco formation.
[m] Number of well doubtful.
[n] Yegua formation, Eocene.
[o] Gas and oil derived from a body of serpentine in Cretaceous strata, at horizon of lower part of Taylor marl.
[p] Gas from sand beneath Tertiary lava flow.

Data on samples of natural gas

West Virginia.

Sample No.	County.	Field.	Well. Name.
C 39	Monongahela		Bowlby well 1

Wyoming.

Sample No.	County.	Field.	Well. Name.
F 5	Big Horn	Lamb dome	Pipe-line sample, five wells
F 6	do	Bryon	Pipe-line sample, three wells
F 13	Carbon	Allen Lake	Cosden Oil Co. well 1
F 14	do	do	do
F 11	Freemont	Big Sand Draw	Producers & Refiners' Co. well 1
F 9	Hot Springs	Buffalo Basin	McFarlane well
F 10	do	Grass Creek	Pipe-line sample
W	Natrona	Emigrant Gap	New York Oil Co. well 1
W	do	do	Curtis Oil Co. well 1
F 1	do	Salt Creek	Pipe-line sample
F 2	do	Powder River	Ohio Oil Co., two wells
F 3	do	Pine Mountain	Pine Mountain Dome Oil Co. well 1
F 7	Park	Oregon Basin	Well 5
F 8	do	do	MacMahon well
F 12	Sweetwater	Dry Lake	John Hay well 1
F 4	Washakie	Hidden Dome	Tensleep well 2

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[a] Probably from Big Injun sand.
[b] Capacity of field.
[c] Frontier formation, Colorado group.
[d] Average depth of wells.
[e] Cloverly formation, Lower Cretaceous.
[f] Casing-head gas.

tested for helium—Continued.

West Virginia.

Well—Continued.					Producing sand.		Date sampled.	Helium (per cent).
Locality.			Rock pressure (pounds per square inch).	Open flow (M cubic feet).	Age.	Depth (feet)		
Section.	Township.	Range.						
10 miles west of Morgantown.			160		Mississippian [a]	1,800	Aug. 18, 1906	0.09
Wyoming.								
			62	[b]19,000	Cretaceous [c]	[d]500	Sept. 10, 1918	Trace.
			350	[b]100,000	do. [e]	1,550–1,840	do.	Trace.
34	23 N.	79 W.			do.	1,357	Sept. 16, 1918	None.
34	23 N.	79 W.			do.	947	do.	None.
10	32 N.	95 W.	1,250	8,000	do.[c]	2,412	do.	Trace.
12	47 N.	100 W.	400	[b]100,000	do.[c]	1,700	Sept. 12, 1918	0.07
			(f)	3,000	do.[c]	[d]700–1,200	do.	Trace.
					do.			Trace.
					do.			Trace.
			(f)	[b]12,000	do.[g]	[d]1,000–2,250	Sept. 5, 1918	None.
			300	2,250	do.[g]	800, 1,267	Sept. 7, 1918	Trace.
36	34 N.	83 W.	200	1,000	Carboniferous [h]	1,668	do.	[i]0.26±
5	51 N.	100 W.	675	16,000	Cretaceous [j]	1,345	Sept. 12, 1918	Trace.
32	51 N.	100 W.	400	3,000	do. [e]	1,300	do.	0.09
20	18 N.	103 W.	40	2.5	do.[k]	2,390	Sept. 16, 1918	Trace.
31	48 N.	90 W.	725	4,000	do. [l]	1,045	Sept. 9, 1918	Trace.

[g] Wall Creek sandstone member of Frontier formation, Colorado group.

[h] Tensleep sandstone or Embar formation.

[i] Sample lost during analysis, but helium content closely estimated.

[j] Greybull sand, Lower Cretaceous.

[k] Dakota (?) formation, Lower Cretaceous.

[l] Colorado group (Frontier (?) formation).

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